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Early Streamer Emission Lightning Protection Systems - Literature Survey and Technical Evaluation

Richard J. Van Brunt
Thomas L. Nelson
Samara L. Firebaugh

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory
Electricity Division
Gaithersburg, MD 20899

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U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Arati Prabhakar, Director

Early Streamer Emission Lightning Protection Systems

Literature Survey and Technical Evaluation

Richard J. Van Brunt, Thomas L. Nelson, and Samara L. Firebaugh[1]
National Institute of Standards and Technology[2]
Gaithersburg, MD 20899, U.S.A.
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[1]NIST summer student, Princeton University, Princeton, NJ
[2]Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce.

Abstract

This report has been prepared by the National Institute of Standards and Technology (NIST) at the request of the National Fire Protection Research Foundation (NFPRF) for the purpose of providing information needed to perform a technical evaluation of lightning protection systems based on the early streamer emission (ESE) concept. Included in this document is an annotated bibliography of over 300 publications that were found to be directly or indirectly relevant to ESE technology. Each publication is listed together with an abstract and/or commentary that describes the nature of the work, and each article in the bibliography has been rated according to its perceived importance. Also included is a discussion derived from an examination of the literature cited in the bibliography about the state of knowledge concerning the operation and effectiveness of ESE devices that identifies issues and areas of controversy. The report concludes with recommendations for research that may be needed to resolve remaining issues.

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I. INTRODUCTION

A. Purpose and Motivation

This report has been prepared by the National Institute of Standards and Technology (NIST) at the request of the National Fire Protection Research Foundation (NFPRF) for the primary purpose of providing scientific and technical information needed as a basis for development and evaluation of possible future standards concerned with the use and installation of early streamer emission (ESE) lightning protection systems. The report includes a bibliography of publications relevant to ESE devices and a discussion about the implications of published results on a technical evaluation of these devices. The ESE devices considered in this report are lightning attractors, and in that sense, their purpose is the same as that of an ordinary "lightning rod" sometimes referred to as a "Franklin rod." The ESE rod differs from the Franklin rod in that it is equipped with a device which supposedly increases the efficiency of lightning attraction and thereby extends the effective range of protection. The term "systems" given in the title is restricted in its meaning to include only the air terminal with its associated instrumentation and controls. The report does not cover issues concerned, for example, with grounding of terminals or with geometrical configurations of multiple-rod arrays.

This report examines the physical bases for ESE devices as discussed in the literature. The discussion and conculsions are based entirely on data, observations, and analyses previously published. No laboratory or field testing or theoretical analysis of ESE devices have been conducted by NIST. An attempt has been made to identify existing areas of controversy and gaps in our knowledge about lightning that need to be considered and addressed in assessing ESE devices.

B. Organization of Report

The report begins with a discussion of how the bibliography is organized and how the items included in the bibliography were selected and rated according to their importance and relevance. The bibliography is annotated in the sense that it includes an abstract and/or commentary about each item listed. The following section of the report includes a discussion of information and issues relevant to ESE technology with appropriate reference to related items listed in the bibliography. The report concludes with recommendations for future work that may be needed to improve the understanding and reliability of methods used to test ESE devices and meaningfully compare their performance with that of other lightning protection systems.

C. Definitions

As an aid to the reader, commonly used technical terms are defined below. It should be cautioned, however, that there is not always universal agreement about the meaning of all terms used here and in the bibliography. For example, in discussions of

lightning discharge phenomena, there is sometimes confusion in the use of the words "streamer" and "leader". Some authors use the term leader where others would insist that they should use streamer. There are also cases where different words are used to denote the same phenomenon. For example, a "corona discharge" is sometimes called a "point discharge"or a "partial discharge". The following definitions reflect the authors' understanding or interpretation as used in this report and no other claim or recommendation is made about universal acceptance.

1. *Early streamer emission air terminal* - Air terminal (lightning rod) equipped with a device that triggers the early initiation of the upward connecting streamer-leader discharge, when compared with a conventional air terminal under the same conditions.

2. *Lightning rod* - A vertical conducting rod used to attract (or intercept) a lightning strike by producing a local enhancement of the electric field strength in air. This is sometimes called a *Franklin rod*, *conventional air terminal*, or *lightning conductor.*

3. *Primary cloud-to-ground (CG) lightning stroke* - The initial discharge between a thundercloud and ground that is generally associated with a stepped leader propagation. Four general types of primary strokes need to be distinguished: 1) downward propagating negative stroke from a cloud negatively charged relative to ground (often referred to as normal lightning); 2) downward propagating positive stroke orginating from that part of a thundercloud positively charged relative to ground; 3) upward propagating negative stroke; and 4) upward propagating positive stroke. The primary CG lightning stroke is also referred to sometimes as the *intitial stroke* or as simply a *lighting flash.*

4. *Stepped leader* - Intense spark or plasma channel of finite but variable length in air corresponding to the observed individual steps in a lightning stroke. This is considered to be a relatively high-temperature discharge stage heated by the passage of an electrical current pulse of high magnitude [136,144,162].

5. *Streamer* - A narrow, highly-directed, and self-propagating discharge in air. A streamer develops from an electron avalanche when the local space charge becomes of sufficient density to produce an electric-field strength comparable to or greater than the external field, and it is believed to propagate at a high velocity by the mechanism of photoionization in high-field regions produced ahead of the discharge. This is a relatively cold discharge phenomenon which can be the precursor to the formation of a leader step [82,136,176].

6. *Return stroke* - This is a discharge that propagates upward from the ground (or lightning rod) in the channel formed by the primary downward stroke. An individual lightning event may exhibit one or more return strokes [159,265]. The return stroke should not be confused with the streamer-leader initiated at a terminal by the advancing primary lightning stroke.

7. *Striking distance* - The distance covered by the last leader step of a downward propagating primary lightning stroke in making contact with a grounded object (lightning

rod). This is sometimes called the *final jump* and it is expected to follow the path of an upward propagating streamer if such a streamer occurs. This distance varies with type and intensity of the lightning stroke.

8. *Corona discharge* - A localized, cold discharge in air that forms around objects such as sharp conducting points or wires which produce an enhancement in electric-field strength sufficient to allow ionization growth. Corona is also believed to form around leader channels. Corona is an important source of space charge at ground level and is sometimes called a *point discharge*, or *partial discharge*. Under some conditions it is the precursor to streamer formation [276].

9. *Zone of protection* - The presumed volume of space surrounding or adjacent to a lightning protection system (conventional or ESE air terminal) that is substantially immune to direct lightning strikes. In the case of air terminals, this could be defined as the volume in which an acceptably high percentage of lightning strokes will attach to the rod as opposed to other locations upon entering this volume. A precise definition of the zone of protection and the methods to be used for its specification and determination are still subjects of debate as will be discussed later in this report [91,96,154].

10. *Cone of protection* - A conic space around a vertical lightning rod used to define a region of protection. This is a cone whose height equals the height of the rod and whose base has a radius centered at the rod and equal in length to the height of the rod. The cone-of-protection concept is based on an electrostatic field calculation [212].

11. *Rolling sphere method* - A method that enables identification of possible lightning attachment points by imaging a sphere of radius equal to the assumed striking distance that is rolled over the exposed surface area surrounding a structure (lightning rod) [154]. Points contacted by the sphere on the surface identify possible lightning attachment locations. It should be noted that, although the method identifies possible attachment points, it does not give information about the probability of attachment to these points [165].

12. *Lightning attraction efficiency* - A measure of the probability that a lightning stroke will attach to an air terminal if it enters its zone of protection, e.g., a 90% efficiency implies that 90% of all strokes that enter the zone will attach independent of their characteristics defined by such parameters as current and angle of approach. There seems to be no clear consensus about this definition; however, the above definition is the one that is adopted in this report.

13. *Onset field* - The electric-field strength above which ionization growth (electron-avalanche formation) is possible in air. This is approximately 2.6 MV/m in dry air at standard temperature and pressure [139].

14. *Time lag* - The time between when the field strength first exceeds the onset field and when a discharge is initiated. Usually a distinction is made between the

statistical time lag (τ_s) corresponding to time of electron-avalanche initiation and the formative time lag (τ_f) corresponding to the the time for complete discharge (streamer or leader) formation. Usually $\tau_f \ll \tau_s$ [177,184].

15. *Space charge* - Density of charged particles (ions) in air that modify the local electric field. The existence of space charge can have a significant influence on lightning propagation.

16. *Thundercloud* - A cloud containing a charge density sufficiently high to allow formation of a lightning stroke.

17. *Cloud-to-cloud (CC) lightning stroke* - A lightning stroke between thunderclouds that may or may not be related to a cloud-to-ground stroke.

18. *Lightning dissipator array* - A system that supposedly repells or diverts lightning by formation of space charge such as from corona discharge generated by an array of sharp metal rods [50,125].

19. *Electron avalanche* - An electron multiplication process due to electron-impact ionization of gas molecules. This is the initial stage in the development of an electrical discharge in air, e.g. a corona or streamer.

II. BIBLIOGRAPHY (Preparation and Organization)

The bibliography that appears at the end of this report contains a list of the published articles that were determined to be either directly or indirectly relevant to ESE lightning protection systems. Included are technical papers that have been published in books, archival journals, conference proceedings, or reports. Each item is accompanied by an abstract and/or brief commentary.

The main criteria for selection are: 1) the work is relevant to understanding the operation and performance of ESE devices; 2) the work is primarily of a scientific or engineering nature and therefore open to comment or criticism in the scientific literature; and 3) the publication is available to the general public. An item was excluded if: 1) it is a report prepared by a manufacturer for the purpose of promoting sale of a product, even if it contained technical data; 2) its purpose is to define specifications for installation and operation of commercial equipment; 3) it was determined to contain proprietary or classified information; or 4) its purpose is to define a standard or is primarily of a legal nature (except for patent documents). The bibliography contains some items that are identified as unreviewed reports or preprints that may have been submitted to a journal or conference for publication. These items have been included with permission from the authors, and copies can be obtained by contacting the authors whose addresses are listed. Patent documents relevant to ESE devices also appear in the bibliography. However, an exhaustive search for patents was not undertaken and only United States patents were considered.

Items have not been excluded because of expressed doubts or evidence against the validity or correctness of the results presented. However, attention is drawn to any published criticisms or refutations of the work either in the discussion or in comments that appear with or in lieu of the abstract. It must be emphasized that inclusion in the bibliography does not imply endorsement by the authors of this report. Even information that appears in archival, peer reviewed publications may be flawed and open to dispute. In a few cases, publications are listed even though their relevance to ESE technology could not be clearly established. The inability to establish relevance may have been due to several different factors such as a failure to obtain a complete hard copy or a complete translation if in a language other than English.

No guarantee can be made about completeness of the bibliography. Work relevant to the topic of this report continues to be published, and it is especially difficult to obtain copies of manuscripts recently submitted for publication or presentation at conferences. There is obviously controversy surrounding the efficacy and utilization of ESE technology as evident from the bibliography and as pointed out in the discussion. It can only be hoped that each side of any controversy has been adequately and fairly represented in this report.

It should be noted that most of the papers included in the bibliography have been published within the last 30 years. Previously published bibliographies on lightning that cover the years before 1980 [4,275] reveal very little work directly concerned with ESE terminals. Some earlier works cited in the literature (especially technical reports prepared by private organizations) could not be obtained and are therefore not listed in the present bibliography even though they would appear to be highly relevant. Most of the technical reports listed were prepared for U.S. Government agencies and are available through the National Technical Information Service (NTIS). With permission, some recent reports prepared for private organizations have been included. It can be presumed that references to most previous work not specifically included in the present bibliography can be found within the works that are included, especially items identified as reviews of the literature.

It is obvious that some of the items listed are more important or directly relevant to the subject of this report than others. As a guide for the user of the bibliography, a recommended priority rating has been assigned to each item. The proposed ratings with regard to relevance plus significance are indicated by the number of asterisks that appear after the reference numbers.

The highest rating, indicated by three asterisks (***), applies to archival (peer reviewed) journal publications, theses, or reports that appear to be concerned directly with tests, evaluations, theory, etc. of ESE devices. Archival papers are assigned the greatest weight regardless of their correctness and regardless of the author's affiliation because it can be assumed that these items are not only readily available, but have also been reviewed by others, and in many cases, subjected to open criticism. A lower rating indicated by two asterisks (**) is given to conference or unreviewed

manuscripts even if the main subject concerns ESE devices. Although comments about unreviewed manuscripts and reports are included, no attempt was made to subject these items to a thorough technical review in this report. It is our judgement that unless a paper has been subjected to a review to which the authors can respond, the results presented therein must be considered preliminary and susceptible to doubt.

Some papers are only indirectly related to the evaluation of ESE systems such as those concerned with models and observations of lightning strokes or streamer initiation and propagation. Indirectly related publications are designated with a double asterisk (**) even if they are archival. A double asterisk is also assigned to patent documents because, although they contain technical information, they are assumed to be primarily of a legal nature and are not generally subjected to the same level of open scrutiny as peer-reviewed papers.

Publications designated with a single asterisk (*) are considered to be of peripheral relevance. Included in this category are papers concerned, for example, with the theory of corona discharges or with the description of lightning simulation and observation facilities. In cases where no indicator of relevance is given, it can be assumed that either the complete article could not be examined or there is reason to doubt its relevance. Even if we were unable to obtain a complete hard copy or translation of a particular item, we included it for the sake of completeness if we had a written summary or abstract in English. In some cases, abstracts originally published in French or German were translated into English. No attempts at translation were made of articles published in languages other than French or German.

Each item in the bibliography includes an abstract as published and/or a comment giving information about the main points and nature of the work. If the item does not have a published abstract or summary, then a brief synopsis or comment was prepared based on an examination of the publication. Information or commentary that is not part of a published abstract is identified under "COMMENT" in the ABSTRACT entry. In most cases the comment is included to indicate the possible relevance of the work to ESE lightning protection systems. In some cases the comment is used to draw attention to historical or controversial aspects of the work such as might appear in discussions or debate published in conjunction with the paper. In other cases it is used to bring to light significant data, remarks or conclusions that appear in the publication but are absent from the abstract.

Items in the bibliographic listing have been sorted in descending alphabetical order according to the last name of the first author. Items for which an author could not be identified are included at the top of the list and entries published by an organization to which an author has not been assigned are given at the end of the list. A complete author index is given at the end of the bibliography. All items listed are assigned numbers which are used in identifying appropriate relevant references in the discussion that appears in the next section.

Units for physical quantities such as propagation velocity, current, etc. that appear in the ABSTRACT are the same as given in the original publication, i.e. no attempts were made to convert units. However, only the International System of units (S.I. units) is used in the discussion and commentary. Identifiable trade names of lightning protection devices or references to manufacturers of lightning protection systems by name that appeared in abstracts, etc. have been deleted from the bibliography and replaced with appropriate generic terms. Cases where such replacements were made are identified in commentary attached to the abstract.

III. DISCUSSION

A. Characteristics of Lightning

The present understanding of lightning has been thoroughly treated in earlier published reviews [95,97,272,274,275,284]. The following discussion only highlights some properties of lightning to which particular attention should be paid in attempts to understand and evaluate the operation of lightning-attractor type protection systems.

Perhaps the most significant properties of lightning that should be kept in mind are its complex, stochastic, and fractal characteristics that make it impossible to predict precisely how a lightning stroke will develop. There can be no such thing as a "standard" lightning bolt. The behavior of lightning phenomena can only be described and analyzed in statistical terms, e.g., by giving probability distributions for stepped leader lengths, striking distances, currents, number of return strokes, angle of approach, etc. as are often found in the literature [36,46,61,111,112,122,170,174,202,264]. No two lightning strokes are ever likely to be the same. Even the prebreakdown, low-level corona discharge phenomena can exhibit complex stochastic and multimodal behavior that is not easily predicted or understood [267,276,277].

Two different types of cloud-to-ground lightning discharges have been identified, namely positive and negative, where the sign refers to the charge at the base of the cloud relative to the charge at ground level. Upward propagating discharges apparently originating at ground level have also been seen with both polarities. In most locations, negative downward strokes are by far the predominant form of lightning. However, recent surveys show that the proportion of positive strokes can be significant (greater than 25%) in some locations, especially in mountainous areas or high latitudes in the northern hemisphere where thunderstorms associated with frontal zones predominate [19,46,199]. The occurrence of positive lightning also varies significantly with season, generally being most common in winter [19,23,122].

In general, the statistical distributions of lightning characteristics vary with terrain, altitude, latitude, and time of year [141]. These variations need to be considered in evaluating or designing a lightning protection system for a particular location. Evidence for significant variability in the behavior of lightning is found not only from

geographical surveys [199,255], but also from numerous observations and recordings at sites frequently hit by lightning such as the CN tower in Toronto, Canada [134], the Empire State Building in New York [46,112,173,174], Mount San Salvatore near Lugano, Switzerland [36,37] and other locations [111,230,232]. The observations performed at such locations have revealed unusual and unexpected behavior of lightning propagation [271]. Although it is known, for example, that lightning often propagates horizontally with respect to ground level within a cloud, as expected [261], there are also recordings of horizontal (or nearly horizontal) propagation over considerable distances at subcloud levels where it is not expected [37,147,185,201,294]. The phenomenon of "ball lightning" [41,164,249,297] may also correspond, in some instances, to a type of horizontally propagating lightning near ground level.

Lightning is generally believed to propagate in the atmosphere by a streamer-leader mechanism [40,136,137,140,144,202,208,233,252,253,283]. Leaders are highly conductive, luminous plasma channels that typically vary in length between 3 and 200 m. The initial lightning stroke is composed of connected leaders or leader steps. The average velocity of propagation of a stepped leader generally fits a log-normal distribution and typically lies within the range of 1.0×10^5 to 2.7×10^6 m/s [264,299], and the electric charge deposited in the leader channel is within the range of 3 to 20 coulombs.

Because of the high concentration of charge in the channel, the electric-field strength produced by the leader can be sufficient to allow electrical breakdown (ionization) of the air at a considerable distance (>10 m) from the tip of the leader. Corona-type discharges develop in the intense field region at the end of the leader from which fast streamers emanate and prepare the path for the next leader step [136,140,252]. When a leader approaches ground level, it can, given a sufficiently high charge concentration in the channel, cause the field strength at grounded conductors such as a lightning rod to become great enough for the initiation and development of a discharge at the grounded site. If a discharge is initiated at ground level, it is likely to propagate upward in the high-field region produced by the leader channel [281]. This is usually the process by which the initial lightning stroke completes its path to ground. The existence of upward propagating discharges that connect with a downward propagating leader has been clearly established from observations in the laboratory of discharges generated under impulse voltage conditions in long air gaps [11,14] as well as from observations of natural lightning [37,92,281]. It should be noted, however, that upward connecting streamers do not always occur (or at least they are not always observed) during a lightning strike to ground [92,274]. Considering the probabilistic nature of the streamer initiation process, it is not surprising that the upward streamer may not always occur, or may be too weak to observe. Moreover, more than one upward streamer can be initiated by the advancing leader at different ground-level locations [241,274], but only one is likely to connect.

The probability that an upward streamer will be initiated at a ground site increases with the local electric-field strength produced by the leader. The instantaneous field

produced by the leader in turn increases with the instantaneous charge and therefore the current in the leader channel at any given time. It can thus be expected, as observed, that for a fixed striking distance from a grounded object, the probability that an upward streamer will be launched should increase with increasing current in the final leader step of the lightning stroke [281]. Also, the mean striking distance to a grounded object should increase with increasing stroke current [6,95].

A typical lightning stroke exhibits a complex branching structure [173,232,275]. This branching comes about in part because of the possibility that, at the end of a stepped leader channel, more than one path may be prepared by different streamers [233]. If this happens, the subsequent leader step can divide and begin to propagate simultaneously in two or more different directions. Only one of the leader channel branches is likely to connect to ground. Cases have been recorded, however, where two or more stepped leader branches simultaneously propagate to ground. In such cases, questions arise about the mutual interaction between branches and the minimum likely branch separation. The theory of lightning is not sufficiently advanced at the present time to account for branching behavior and the general fractal dimensions of lightning. The space-charge distribution in the atmosphere below the cloud is also likely to influence the branching characteristic [96]. It is only relatively recently that fractal models of electrical-discharge phenomena have been introduced that deal with the branching characteristics [194,195].

There is still much that we do not understand about the behavior of lightning, and the physics of lightning remains a topic of intensive scientific investigation at research laboratories around the world [16,54,87,119]. Little is known, for example, about the mechanisms by which a lightning discharge is initiated within a thundercloud [103,279]. The average electric-field strength in a cloud generally lies far below the breakdown strength of air. The initiation of lightning is possibly associated with local enhancements in the charge density within the cloud. In any case, there is reason to believe from observations of lightning propagation within clouds [146,294] that a cloud from which lightning originates cannot be treated as a uniformly charged equipotential region. Moreover, it has been argued that objects at ground level cannot influence the triggering of lightning in a cloud [56,181]. This is a reasonable expectation because the region of a cloud from which lightning originates is likely to be at an altitude of 3 to 4 km above ground level which is one to two orders of magnitude higher than most grounded objects. Thus, any claims made about the ability of a ground-based lightning protection system to trigger or attract lightning strikes from a cloud should be viewed with skepticism. An exception, of course, is the use of ground-launched objects such as aircraft or rockets that are known to trigger lightning [21,193].

Another area of active lightning research that deserves special attention is that concerned with the influence of local space charge on the path of a lightning stroke. It has already been shown from laboratory simulations [292–294] that discharge propagation can be affected significantly by the presence of space charge associated with

ions or charged particles. Space-charge effects are expected to be significant within a thundercloud, but may also be important at ground level where ions can be produced by corona or point discharges that occur in advance of a lightning strike [27,55,56,97,187,197]. The presence of space charge could influence the performance of a lightning protection system and may explain the occurrence of horizontal or other unusual forms of lightning [96]. Research is still underway and needed on factors that influence the electric-field distribution at ground level under a thundercloud [133,146,148,248,257].

B. ESE Air Terminals

An early streamer emission air terminal differs from a conventional air terminal or lightning rod in that it is equipped with a device that supposedly enhances the probability of initiating an upward propagating discharge (streamer) to connect with the downward propagating leader of a lightning stroke [300]. This enhancement presumably applies for both polarities of natural lightning, although discussions about the polarity dependence of ESE systems seems to be noticably absent from the literature. An ESE terminal can often be distinguished from an ordinary lightning rod by the presence of a small object near the top of the rod that serves as a discharge trigger [8]. The geometrical configuration of the rod tip for ESE rods can also be more complex than that of a conventional rod [8].

There are different types or designs for ESE terminals. A common feature in the operation of all is that they utilize a discharge triggering device to increase the probability for initiating a streamer discharge at or near the rod tip upon approach of a decending leader. Contrary to some misconceptions, ESE terminals do not significantly increase the conductivity of air at a considerable distance (>10 cm) beyond the tip of the rod [53,225]. Possible exceptions are systems that utilize intense laser beams to "guide" a leader discharge. However, such devices are considered to be experimental, and at the present time, are not known to be used for practical lightning protection. The main attracting effect of an ESE terminal is undoubtedly due to the metal conductor itself that introduces a significant enhancement of the electric-field strength which, in turn, increases the rate of ionization in the air around the rod above that at other nearby locations. In so doing, it increases the probability of discharge initiation and perhaps also the speed with which the discharge can propagate compared to surrounding areas that are at a lower field. A tall lightning conductor can therefore compete more favorably in attracting a lightning discharge than conductors in the same vicinity of smaller height [57,239]. Like conventional terminals, the attraction efficiency of an ESE terminal should increase with its height above the ground up to a limit determined by the maximum striking distance.

Three general types of ESE devices have been identified, namely: 1) rods to which a radioactive source is attached, also referred to as *ionizing* or *radioactive air terminals* [38,108,109]; 2) rods equipped with an electrical triggering device [8,155]; and 3) systems that use laser beams [18,22,243,270]. Of these only the first two types are

currently in use. The third type is still under development and its effectiveness, although promising, has not yet been demonstrated outside of the laboratory.

The most widely used, and perhaps most controversial ESE device is that equipped with a radioactive source positioned near the top of the terminal [38,58,59]. The radioactive materials employed are weak alpha particle emitters with relatively long lifetimes such as ^{241}Am used in some smoke detectors (half life = 458 years). Other types of radioactive materials have also been used including ^{210}Po, ^{226}Ra, ^{85}Kr, and ^{60}Co [180]. The products from radioactive decay of these materials ionize the air in the immediate vicinity of the terminal, typically within a radius of 1 to 3 cm. The ion-pair production rate can be as high as 10^{12} per second. It has been argued that, outside of a small region near the terminal, the ion pair formation rate in the atmosphere from the radioactive source will fall significantly below the rate from natural background radiation [225]. Evidence that radioactive air terminals are superior to conventional Franklin rods has been reported based on interpretation of results from outdoor tests using impulse breakdown of rod-plane gaps [114-118]. However, many questions have been raised in the literature both about the effectiveness of radioactive air terminals [17,26,42,47,48,53,62,91,94,157,165,187,215,216,225,245,278] and about the potential hazards they pose because of possible human exposure to harmful radiation [24,25,39,89,167,180,196,278]. In some countries their use is prohibited by law [155].

In recent years, ESE terminals that use electrical triggering devices have been introduced. In principle, their purpose is the same as a radioactive source, and there is no reason to believe that electrically triggered systems could not be at least as effective as a radioactive air terminal. They offer the potential advantage of more control over ion production at the tip of the terminal and thus would appear to be more effective in avoiding unwanted continuous corona discharge formation in advance of a lightning strike. They also avoid the health and environmental issues that are associated with radioactive devices. Nevertheless, very little information could be found about electrically triggered ESE systems in the archival literature. Most of the discussion about these devices is confined to patent documents [155] and to relatively recent conference papers [8,9,28,29,30,32,34]. The available information is usually both of a preliminary nature and lacking in technical details. Consequently it is impossible at this time to make a complete, independent assessment of the performance of ESE terminals that employ electrical triggering.

From the limited information published about such devices, it appears that they employ a detector that senses the approach of a downward propagating leader by producing an electrical signal proportional either to the electric field or the rate-of-change of the electric field produced by the approaching leader [8,155]. When the output signal of the detector reaches a certain level, it triggers a circuit that then applies a fast, high-voltage pulse or pulses either directly to the rod or to a spark gap electrode arrangement positioned at the top of the rod. The application of the electrical pulses enhances the field enough to create a local discharge or ionization

at the most opportune time to initiate an upward propagating streamer directed at the oncoming leader. Thus, unlike a rod equipped with a radioactive source which causes continuous ionization in the surrounding air, the electrically triggered ESE device produces ionization only during a brief period prior to the lightning strike. Information about the duration and extent of this ionization could not be found.

There are other types of recently developed ESE terminals that utilize the piezoelectric effect for electrical triggering. Although this type of terminal is now available commercially, only scant mention of it is made in the archival literature [49,155]. From an examination of the literature, we decided that there is insufficient published information about the operating principles and performance of the piezoelectric devices to enable an independent appraisal of their performance. It is presumed that the function of a piezoelectric trigger is the same as other ESE devices, namely to enhance ionization and thereby increase the probability (reduce the time lag) for initiation of an upward propagating streamer directed at an oncoming lightning stroke.

As mentioned above, lightning protection systems that utilize laser beams to trigger and/or guide a lightning discharge, or to assist in launching an upward streamer are considered to be experimental. At the present time, there are no known commercial systems that employ lasers. Laboratory studies have shown, however, that laser beams can be effective in initiating and controlling the path of an electrical discharge in long air gaps [7,88,100–102,121,123,129,131,132,178,191,240,242,243,259,296,298].

The comparative advantages and disadvantages of the different types of ESE devices in terms of their cost, size, reliability, etc. have not been examined in this investigation. The fact that there are competitive ESE devices available with differing configurations and operating principles should be of concern in proposing new standards for lightning protection systems. It is doubtful that the efficiency and reliability of performance is the same for all types of ESE terminals.

In the following three sections the physical bases for ESE devices are examined and issues related to the validation or verification of ESE device performance are discussed.

C. Physical Bases for ESE Air Terminals

A complete assessment of ESE air-terminal performance requires an understanding of the basic physical mechanisms responsible for their operation. It is not clear from an examination of the relevant literature that there is a complete and universally agreed upon understanding of how or why these devices work. In the case of ESE terminals that use radioactive sources, arguments are made in the literature that they simply do not work, or are at best relatively ineffective [17,42,48,94,157,165,215,216,245,278]. These negative opinions are usually based on a lack of evidence that could be found in the literature about the performance of radioactive terminals, and are seldom based on results of independent tests. Reliable quantitative data about the relative performance of ESE versus conventional devices under relevant conditions are definitely

lacking. However, the of lack data does not necessarily prove that ESE devices do not work. The questions that should be asked are, how do they work and how much better do they work, or could they work than conventional terminals, i.e., what is the gain, if anything, in lightning attraction efficiency? No indisputable results were found that can presently answer these questions.

Taking into consideration what is presently known from laboratory studies of relevant electrical-discharge phenomena, reasonable speculation is possible about the important processes that can account for ESE device operation. Unfortunately one must resort to speculation or extrapolations from laboratory scale experiments because there is a dearth of detailed information from observations made during lightning strikes in the natural environment.

The one characteristic that appears common to all types of ESE devices is that they enhance ionization of the air in the immediate vicinity of the terminal tip prior to an approaching lightning stroke. This additional ionization presumably enhances the probability that an upward propagating streamer will be launched from the terminal tip. A legitimate question that could then be asked is, how does this additional ionization act to enhance streamer formation?

The answer to this question is not obvious but would appear to be found from a consideration of the *time lag* to electrical breakdown that has been the subject of numerous laboratory investigations discussed in previous reviews [184]. In order for an electrical discharge (streamer) to be initiated after a rapidly rising voltage has been applied, for example to a point-sphere or sphere-sphere electrode gap in air, so that the electric-field strength exceeds the breakdown strength of air, there must be at least one free electron available to initiate the electron avalanche process which is the precursor to streamer formation [82,136,150,171,184]. In the case of a positive point electrode, which approximates the conditions of a normal negative lightning stroke, the initial electron release mechanism is thought to be due primarily to the process of collisional electron detachment of negative ions [184,246]. The rate of collisional detachment depends both on the type of negative ion and on the strength of the electric field in which it moves.

In the case of air, the types of negative ions that can be formed depend significantly on water-vapor content (humidity) and this appears to account for the observed large difference in laboratory measured time lags for dry and humid air under positive impulse conditions [13,104,145,179,289]. From laboratory experiments on positive impulse breakdown in air, it is usually found that measured time lags exhibit a pronounced decrease with increasing humidity, i.e. the discharge initiation probability is enhanced by the presence of water vapor [184,226]. Negative ions in the atmosphere are formed by attachment of low-energy electrons to electronegative gas molecules such as O_2 and H_2O. Initially formed negative ions such as O^-, O_2^- and OH^-, can undergo transformations into other types of negative ions such as O_3^- and $OH^- \cdot H_2O$ through a complex sequence of ion-molecule reactions [276].

The presence of negative ions in an electrode gap prior to the application of an impulse voltage (simulating an approaching leader) does not guarantee that a discharge will be initiated. For example, if the rate of voltage rise is too slow, the ions may simply be swept out of the gap before undergoing detachment. Moreover, the field strength at which a negative ion can detach an electron may, depending on the type of ion, lie above or below the breakdown field strength of air, and this will determine its effectiveness in intitiating a discharge. If the ESE device helps ensure the presence of negative ions near the terminal during the approach of a lightning stroke, then it could be effective in reducing the time lag for streamer initiation. However, its effectiveness must be measured against naturally occuring time lags and might depend significantly on such conditions as relative humidity and total charge (strength) of the oncoming leader in the lightning stroke.

In the case of a negative point electrode, as occurs for positive lightning, the discharge initiation mechanism can be quite different. Near a negative point, detachment of negative ions may still play a role; however, these ions will be forced to move into the lower field region away from the the electrode tip where detachment by collision with air molecules becomes less probable. For negative points, the inititiatory electrons can also be released by collision of positive ions with the point electrode surface. The effectiveness of preleader ionization in enhancing streamer initiation at the tip of an air terminal can be expected, therefore, to have a polarity dependence. The extent to which streamer initiation probability depends on polarity for a given ESE or conventional terminal is generally not known, or at least there is no evidence in the archival literature that it has been investigated thoroughly.

It should be realized that the presence of ionization at the terminal tip in advance of a lightning stroke can also act to undermine the effectiveness of an ESE device if this ionization can occur under high enough field strength to allow formation of a corona discharge [15,114,141,171,172]. Once a corona forms it produces orders of magnitude more ions than can be generated, for example, from alpha particle emission from a radioactive source. The presence of ion space charge can significantly reduce the electric-field strength near the top of an air terminal and thereby act to inhibit streamer initiation [203,267]. The possiblity of corona formation depends on different factors such as the geometry of the terminal [262]. It has also been shown conclusively from experiments performed in the atmosphere that the intensity of a corona discharge and the density of space charge associated with it depends significantly on local wind velocity [151,248].

Laboratory experiments performed to determine the influence of radiation on the initiation of air discharges in large sphere-plane gaps have shown that the presence of the radiation increases the likelihood of discharge formation for impulse voltages with steep wavefronts, but decreases the likelihood for breakdown at longer wavefronts (1 μs compared to 180 μs) [12]. For steep wavefronts the breakdown voltage is therefore effectively lower than it is for longer wavefronts. This experiment seems to show that the presence of radiation enhances discharge initiation provided there is in-

sufficient time for corona space-charge formation. However, the effect of the radiation was, in either case, relatively small and the source and role of corona generated space charge were not quantified or even clearly identified. One of the conclusions given in this work is that the major effect of the radiation and corresponding ionization of the air is to eliminate very long time lags to sparkover. It should be kept in mind that time lag is a statistical variable, and for a given well-defined set of discharge gap conditions there will exist a distribution in time lags that can be determined experimentally [184,246].

It should also be noted that corona discharge formation is invoked to account for the effectiveness of supposed lightning dissipators [47,50,104,125]. In this case, corona discharges presumably form at a multitude of sharp conductors positioned around the area to be protected and thereby produce enough space charge to reduce the electric field and deflect the path of oncoming lightning. The formation of corona can depend significantly on the water-vapor content of the air around the terminal [98,145]. The issue of corona formation is also central to the debate about the most desirable shape for the end of a conventional lightning rod [106,107,125,181,183,189]. Blunt rods are reported to perform better than sharp rods in attracting lightning, supposedly because corona forms less readily around blunt rods than around sharp rods [189]. The issue of corona formation is also relevant to the operation of ESE devices and is presumably a factor that is considered in the geometrical design of such terminals. Details of how ESE devices are designed to avoid corona formation prior to a lightning strike are not discussed in the archival literature.

In addition to ion formation that occurs during discharge activity near the tip of a lightning rod, electron and ion collisions with atmospheric molecules can form relatively long-lived metastable excited neutral species such as the $a^1\Delta_g$ electronic state of the oxygen molecule or the $A^3\Sigma_u^+$ electronic state of the nitrogen molecule. Additionally, vibrationally excited metastable molecular species are produced in a gas discharge. The presence of these metastable species can have a significant influence on streamer-discharge propagation because they are more readily ionized than air molecules in the ground state and because they can supply energy to electrons by superelastic collisions, the overall effect of which is to provide a path of lower resistance to an oncoming discharge [35,113,163]. The quenching of metastable species through collisions with other molecules or with surfaces can also be a source of discharge initiating electrons, i.e., their presence under some conditions might be effective in enhancing the probability of discharge inception [277].

Unlike ions, neutral metastable species do not contribute to modification of the local electric-field strength and their motion is also not significantly influenced by the presence of a field. They tend to diffuse away from their point of origin, and their effectiveness in modifying a discharge path and their range of influence depends on their excitation energy and density distribution at any given time. The metastable density distribution depends, in turn, on the relative rates of formation, quenching, and diffusion of these species. Although the influence of metastable species on discharge

development has been established from laboratory investigations [113], considerably less is known about the dynamics and interactions of these species in a discharge compared to what is known about ions. In particular, very little is known about how they contribute to lightning discharge initiation or propagation under relevant atmospheric conditions. As with negative ions, the metastable content of the air around a lightning terminal will be affected by relative humidity and general air contamination. The influence of metastable species should not extend significantly beyond the end of a lightning rod. Their role, if anything, will be to enhance initial development of a streamer at the rod tip.

In summary, it would appear that enhancement of upward streamer initiation from an ESE terminal (compared to a conventional terminal) has a plausible physical basis. However, it would also appear that a complete and universally accepted understanding of how all ESE devices work has not yet been achieved, and it can be argued that a better understanding is needed to make meaningful quantitative comparisons between the performances of ESE and conventional devices. To reach such an understanding it will undoubtedly be necessary to address numerous basic questions such as:

1. What are the predominant streamer initiation mechanisms under different conditions of polarity, atmospheric humidity, air contamination, and terminal geometry?

2. What are the relative roles of ions, electrons, and metastable species on the development and propagation of a streamer discharge from a terminal for different conditions?

3. What is the likelihood of corona formation around a terminal and how will the presence of corona affect the ability of the terminal to launch a streamer upon approach of a lightning stroke?

4. In the case of radioactive terminals, what is the dependence of the streamer initiation probability on the intensity and type of radiation source?

5. In the case of electrically triggered devices, how does the streamer initiation probability depend on the timing and magnitude of the electrically triggered spark?

6. Also for electrically triggered devices, how reliable is the field sensor that controls the triggering, and can its performance be affected by local space charge?

Attempts to find answers to questions like these are the focus of much ongoing experimental and theoretical research, not only on lightning, but on electrical discharge phenomena in general.

D. Validation of ESE System Performance

Three general methods have been used to evaluate and test the performance of lightning protection systems, namely: 1) small-scale laboratory or outdoor tests in which lightning, or the effects of lightning are simulated by applying high-voltage impulses

to widely separated electrodes; 2) theoretical simulations of lightning strokes that predict propagation behavior and striking distance; and 3) outdoor tests involving observations of artificially triggered or naturally occurring cloud-to-ground lightning strikes. In this section we briefly examine the advantages, disadvantages and issues that have been raised concerning the use and validity of these methods.

1. Laboratory and small-scale tests

Considerable insight has been gained about the physical nature of lightning from laboratory-scale studies of electrical breakdown and spark formation in "long" air gaps, with typical gap spacings of 2 to 15 m [9–12,198,207,238,263,268,287,289]. Long air gaps have also been used to test the performance of lightning rods, including ESE devices, both in enclosed laboratory space and in the open outdoor environment [29,30,32,83,114–118,241]. An obvious critcism of such tests is that even a 15-m gap is two orders of magnitude or more smaller than the height of a cloud above ground from which a typical lightning stroke originates. Such a large extrapolation has been considered by some to be unacceptable and essentially renders laboratory-scale tests useless in evaluating the performance of a lightning rod [93,251].

It can be argued, however, that for the purposes of testing and research on lightning rod performance, it is probably not necessary to simulate an entire cloud-to-ground lightning stroke in the laboratory. It is only required that a realistic simulation be made of the final leader step in the stroke that approaches a lightning rod [83,251]. This reduces the scale and simplifies the problem enormously, but still leaves a formidable task that taxes the limitations of present day laboratory facilities. For example, in order to simulate the entire range of striking distances likely to occur in the natural environment, it would be necessary to perform tests using electrode gaps in excess of 100 m. The gaps presently available in the largest laboratories are smaller than this by roughly an order of magnitude. Although some gain in gap spacing can be achieved by going to the outdoor environment [287], one still encounters the limitations on voltage imposed by existing impulse generators. Even in the largest laboratories in which ESE devices have been tested there is no provision to simulate all of the conditions under which lightning occurs in the natural environment. It will be recalled that natural lightning exhibits significant statistical variability in such parameters as current, mean striking distance, and angle of approach with respect to any vertical lightning conductor. It also usually occurs under conditions where significant space charge may be present due to local point discharges and where humidity and surface moisture levels are relatively high. Moreover, high winds also tend to be associated with the occurrence of lightning. It must be recognized that such parameters as humidity, space charge, and wind are not independent of one another. For example, the rate of space charge development is expected to depend on humidity and the wind will be effective in redistributing the space charge once it is formed [248]. Although the influence of factors such as space charge [302] and humidity [289] have been investigated in the laboratory tests, it is not clear that the myriad of conditions which can exist in the natural atmosphere during a thunderstorm have been or can

be adequately simulated in present laboratory facilities. The extent to which it may be necessary to simulate all conditions is certainly a subject for debate.

Another concern about validity of small-scale simulation has to do with the degree to which the discharge produced is really like that of lightning. There is evidence, for example, that the current and propagation velocities of laboratory-generated leaders differ considerably from those associated with natural lightning. It would appear that more investigations into comparisons between the properties of simulated and natural discharges may be required before more reliance is placed on laboratory scale testing to evaluate the performance of air terminals. The adjustment of laboratory parameters to produce long sparks that match the characteristics of natural lightning assumes a complete knowledge about the characteristics of natural lightning. The extent to which our knowledge of lightning is sufficiently complete is still open to debate. The similarities and differences between natural lightning and long sparks produced in the laboratory have been extensively discussed and debated in the literature [66,73,85,86,90,93,107,116,126,127,135,152,211,250,251,256,273,282,283].

Despite the present limitations, laboratory tests coupled with fast electrical and optical diagnostics probably offer the best means for learning about the physical mechanisms, operation, and performance of lightning protection devices in a reasonable time frame. Laboratory tests are especially useful for investigating factors that influence streamer initiation from an air terminal, and there seems to be much that can be learned about the initiation and initial discharge growth process for both conventional and ESE terminals. Many laboratories have been set up to simulate different aspects of lightning [51,52,60,77,79,204,234,235,236,285,301,302], and even though most of them are not designed specifically for testing lightning protection devices, some of the advanced diagnostic methods developed in these laboratories might find application in air terminal testing.

Because of the large statistical variability in lightning behavior, there is unlikely to be a single acceptable test configuration that can be used to completely characterize the performance of all lightning protection devices. In the future, it will probably be necessary to consider a set of laboratory test configurations that represent the range of lightning behavior likely to be encountered in the environment. At present it would seem that we are a long way from having a standard laboratory test procedure for lightning protection systems. The influences of such parameters as moisture, space charge, and wind are still topics for research.

It is recommended that caution be exercised in drawing significant quantitative conclusions about the comparative performances of different lightning protection systems in the natural environment from small-scale tests. There would especially be reason to doubt results from simultaneous tests of two or more devices that are placed in close enough proximity to be within each others supposed range of protection. Under such conditions, the presence of one device can significantly modify the electric field configuration of another device (and vice-versa) and thereby affect its performance.

2. Simulations using theoretical models

With the advent of high-speed computing, it has become feasible to consider the use of theoretical simulations of lightning as a tool in evaluating the performance of a lightning protection system. In the past 20 years, considerable progress has been made in understanding the mechanisms of electrical discharge initiation [99,139,142,143,172, 203,228,286,299] and in the modeling of corona streamer-leader discharge propagation in both small and long air gaps [40,63,71,74,128,153,166,168,169,192,214,227,275]. Nevertheless, the theory of lightning is still in the developmental stage and new results continue to appear in the literature. At present, a "standard" model for the lightning discharge does not exist. The existing models employ many simplifications and approximations that cannot be examined or critiqued in this report. It suffices to say that they are generally designed to account best for laboratory-scale observations of long-gap spark development in air and have not reached the level of sophistication required to account for the broad range of complex statistical and fractal behavior characteristic of natural lightning. Even phenomena as simple as electron-avalanche development and corona are known to exhibit complicated stochastic behavior that has only recently been dealt with in theoretical models [276,277,286].

In as much as the effectiveness of ESE devices is attributable to their ability to enhance initiation of an upward streamer in the field of an advancing leader, models used to estimate their performance compared with conventional terminals must necessarily deal with the statistics of discharge initiation, i.e. they must be capable of predicting time lags applicable to environmental conditions of the terminal. Unfortunately, the problem of statistical time lags is very complex and is generally avoided in existing computer models of discharges. The complexity of the problem is due in part to a lack of knowledge about microscopic processes of initiatory electron release and the statistical behavior of electron-avalanche growth in nonuniform electric fields, particularly under the multitude of conditions that could be encountered at the tip of a lightning terminal.

The one area where existing theory presently shows promise for evaluation of lightning terminals is in the prediction of striking distances [6,64–66,68,72,75,218–223,247,263, 266]. Assuming that the electric-charge distribution within the approaching leader step is known, estimates can be made from electrostatic-field calculations of the instantaneous field at a nearby conductor, e.g., a vertical conducting rod. Assuming a relatively simple charge distribution in the leader channel, e.g., a linearly uniform cylindrical distribution, it is often possible to express the field at the terminal due to the leader in closed form [219]. Calculations of this type which take into consideration the wide range of possible leader conditions (defined by such parameters as charge, length, and position) could be useful in estimating the maximum ranges of protection [281]. In essence, such calculations, when coupled to the streamer inception criterion [29,59,63,74,150,176,205,213], determine the locations where an advancing leader produces an electric-field strength at the terminal tip sufficient to allow streamer development. It must be understood, however, that such calculations

supply geometrical information that is applicable to all terminals of the same general geometrical configuration independent of whether or not they are equipped with an ESE device. In this respect, they do not yield specific information about performance of the ESE device itself unless the device operates in such a manner that an impulse voltage is applied to increase the potential of the terminal conductor tip relative to ground during the approach of a lightning stroke. Such a voltage would create a field that adds to the leader field thereby increasing the presumed maximum range of protection. (It is not clear that any electrically triggered ESE devices actually do this, and if they do, no information could be found in the literature to indicate that calculations of the type mentioned above have ever been performed).

Criticisms that can be raised about present striking distance calculations relate to their semi-empirical nature and the fact they assume leader charge distributions that may be unrealistic or have not been confirmed by observations of actual lightning discharges. Moreover, these calculations have not dealt with effects of atmospheric space charge near ground level. Validation of lightning models by comparision of calculated results with observations made during natural lightning strikes presents a major challenge to theorists. A complete model should account for all observed properties of lightning such as measured current, optical and radio-frequency emission spectra, propagation velocity, etc. The challenge is made especially difficult by the broad statistical variability in lightning behavior and the sparsity of complete sets of observations on single lightning strokes that have been reported up to the present time. Nevertheless, it would appear that the method of predicting striking distances by simulating the effect of an approaching leader shows great promise and it should be pursued and improved upon. It possibly offers the best approach to answering some of the difficult and controversial questions associated with realistic determinations of protection zones that will be discussed later in this report.

3. Tests using natural or artificially triggered lightning

Perhaps the easiest and least controversial method of testing lightning protection systems is to observe their performance in the natural environment during actual thunderstorms. However, this approach is neither as easy nor as lacking in controversy as it may first seem. First of all, with the exception of unusally high towers such as the Empire State Building, lightning strikes to any given location in relatively flat terrain where a lightning rod is positioned are likely to be extremely infrequent [200]. Even in places that experience a high rate of lightning strikes such as in some parts of central Florida, the number of recorded cloud-to-ground strokes within a square kilometer is likely to be less than five per month on average [199,210] during the peak of the thunderstorm season. Clearly, if natural lightning strikes a terminal only one or two times per year, it takes an extremely long time to acquire enough data on its performance to be statistically meaningful.

Recent attempts to test air terminals positioned at high elevations on mountain tops in New Mexico where there is a known high frequency of lightning have shown that

lightning seldom hits a terminal regardless of whether or not it is equipped with an ESE device [182,183,215]. Although a few isolated strikes to the mountain were reported to have occurred within the supposed zones of protection of ESE terminals [183,215], it would appear that the overwelming majority of strikes to the mountain were at considerable distance from any terminal. In any case, the failure of air terminals to attract lightning on mountain tops at elevations of 3000 m (9843 feet) or more is obviously disturbing and raises questions about the interpretation of such observations. Before any serious conclusions are drawn about the performance of lightning attractors from tests performed on mountain tops, it may be necessary to consider the perturbing effect of the mountain itself on such parameters as the surface charge distribution and electric-field profile under a thundercloud, as well as the extent that lightning strokes at such high elevations differ from those that normally occur in lower, flatter locations. It would appear that the answers to some of these questions might already be found in the literature.

It is noted in some papers that lightning that occurs at high elevations generally differs on average from that which occurs at sea level, if in no other respect than that it has less distance to cover in going from the cloud to ground [36]. At an elevation of 3000 m, the ground can be quite close to or even engulfed by the base of a storm cloud. Certainly the results from high mountain tests cannot be dismissed, and such tests should continue, as should similar tests underway at other locations [107]. The problem is how to interpret the results of these tests and infer what they might imply about air terminal performance at lower elevations, and what they indicate about the influence of mountainous or rocky terrain on the effective zone of protection of an air terminal.

The unfavorable statistical odds associated with natural lightning can be partially overcome by using artificially triggered lightning. Tests have shown that lightning can be triggered with reasonably high probability by a rocket launched into a thundercloud [124,160,190,193]. A long trailing wire is usually attached to the rocket which provides a low resistance path to guide the initial discharge and define its direction of propagation [45,120,193]. Transportable facilities have been developed for rocket triggering of lightning that can be used for testing at nearly any location [231]. Although tests of air terminals are being made using triggered lightning, there are questions that can be raised about the meaning of such tests. There is evidence that triggered lightning is unlike natural lightning both in its intensity and propagation characteristics. In particular, it has been noted that triggered lightning is of lower current than natural lightning and exhibits characteristics more like those of return strokes observed in natural lightning [78,161]. It has also been argued that triggered lightning does not satisfactorily mimic the primary stroke and is therefore unsuited for investigation of the attachment to a grounded lightning conductors, i.e. its use in evaluating air terminals would appear to be questionable [78]. The extent to which rocket-triggered lightning behaves like natural lightning seems to depend on the length of the trailing wire and the distance of the bottom end of the wire above

ground when the discharge occurs. Notwithstanding valid criticisms, essentially no quantitative information could be found in the literature about results from tests performed on air terminals using artificially triggered lightning [76].

Even though testing of air terminals using natural lightning has obvious limitations, we would recommend long-term or continuous monitoring of lightning around air terminals during thunderstorm activity. Data from such monitoring could prove valuable in identifying conditions under which lightning protection devices are likely to fail. Admittedly it is difficult to draw meaningful conclusions from isolated events, but it can be argued that previous lightning records [107,147,255,264] have already proven useful in revealing unusual forms of lightning behavior that ought to be considered in designing laboratory methods or computer simulations for use in evaluating lightning rods.

E. Issues to be Addressed

In concluding this discussion we draw attention to four specific issues or points of controversy that require attention. For purposes of evaluating the relative performance of ESE and conventional air terminals, the first of these issues would appear to be by far the most important. The second issue is connected with the first in the sense that there may exist uncontrollable factors that affect the zone of protection offered by a terminal regardless of whether or not it is equipped with an ESE device.

1. Zone of protection

The classical "cone-of-protection" concept often used to specify the region of space that is supposedly protected by a lightning conductor was first introduced in the 19th century and is based on rather simplistic electrostatic field analysis using a rod-plane type geometry in which the base of the thundercloud is assumed to have a uniform charge distribution [188,212]. More recently the "rolling sphere" method has been introduced [48,154,165,189] to estimate protection zones. Although this method can be viewed as an extension of the cone-of-protection concept, it goes beyond this concept in providing identification of possible attachment points within the cone, e.g., the rolling sphere method allows for possible lightning strikes to the side of the Empire State Building, whereas the cone-of-protection specification does not.

These concepts, despite their simplicity, can be used as a rule of thumb for making first order estimates of protection zones around a lightning rod or an array of lightning rods [31,48,91,189,244,295]. However, we would judge that the zone-of-protection estimates derived from electrostatic field calculations are a likely source of misunderstanding and are susceptible to misinterpretations that can lead to claims about the protection capabilities of air terminals (regardless of whether or not they are equipped with an ESE device) which may be exaggerated or unrealistic.

Recognizing that lightning is a stochastic process that exhibits a broad range of behavior, it has been recommended that the simplistic zone-of-protection concept be

replaced with a more realistic statistical description in which, for example, the most probable (or maximum) striking distance is displayed graphically as a function of leader or primary stroke current [43,95,218,254]. It has been noted that striking distances for positive discharges will differ from those for negative discharges, and that the knowledge about positive striking distances is inadequate [96]. Nevertheless, enough may now be known about the behavior of lightning and the lightning attachment process that more sophisticated and statistically meaningful statements can be made about protection zones than are used presently [66,175,281].

Recently developed models for calculating striking distances [6,59,65,72,149,218-223, 247,263,266] could prove useful, for example, in determining the maximum distances from a terminal at which leaders with particular characteristics (length, charge distribution, and velocity) could enhance the local electric-field strength enough to allow development of an upward streamer. Such calculations place an upper bound on the size of the protection zone for a terminal with a given geometry (height) independent of its ESE characteristics [84]. Given knowledge (or assumptions) about enhancement of streamer initiation probability at an ESE terminal for a particular local field strength, it is conceivable that reasonable quantitative estimates could be made of the incremental increase in lightning attraction efficiency of ESE terminals over conventional terminals. No evidence could be found that this type of analysis has ever been attempted for ESE terminals. Most of the theoretical work on striking distance has been motivated by the concerns of electric-power utilities about lightning strikes to power transmission systems [68,84,97,154,218-223]. Much of what has been learned from the ultility work can undoubtedly be applied to an evaluation of air terminals.

2. Uncontrollable factors

One of the most difficult problems faced by those who design and test air terminals are those associated with assessing the influence of uncontrollable factors. Included here would be effects of nearby objects such as trees, buildings, smoke stacks, etc. The presence of these objects may not only be sources of corona and therefore space charge [130,248], they may also significantly perturb the electric field within the specified zone-of-protection. In addition to nearby objects, the terrain itself can also be a factor in determining realistic zones of protection. If the effective zone of protection is extended such as through the use of an ESE device, then problems of assessing the influence of other objects and variations in terrain are also extended.

Additionally, flying debris in the vicinity of an air terminal (dust, leaves, sticks, paper, etc.) may be of concern, particularly if it can somehow attach to the terminal. This concern is justified because high winds often associated with thunderstorms stir up and elevate ground matter and because the more complex geometries used in the construction of ESE devices may offer greater opportunities for trapping ground matter. The effect of flying debris is an issue that seems to be ignored in the literature. On the other hand, no evidence could be found to suggest that this effect is responsible for any failures of air terminals to attract lightning.

3. Radiation hazards

In the case of ESE devices that employ radioactive materials, issues have been raised in the literature about the possible radiation hazards to humans that the use of these devices present [24,25,39,81,180,196,278]. As noted above, radioactive air terminals are banned in some countries, presumably because of perceived health hazards. It has been noted that ^{241}Am sources used in lightning protection devices are not any more hazardous than similar sources approved for use in smoke detectors or static eliminators [109,167,180]. Nevertheless, there are those who argue that the public may be placed at risk from a proliferation of radioactive materials in devices that can enter the environment without adequate controls [25,81,180]. An evaluation of the health and safety aspects of radioactive sources used in air terminals lies outside the scope of this report. However, we have identified this as a serious issue that the manufacturers and users of radioactive terminals must be prepared to address.

4. Damage and maintenance

Given that ESE devices likely have a structure and associated instrumentation that are more complex than conventional air terminals, questions can be raised about their susceptibility to damage during a lightning strike. The electric current and energy deposited by a lightning stroke can be sufficiently high to actually melt metallic structures and destroy electronic components. There are numerous reports of damage inflicted by the primary lightning stroke to metal parts on aircraft, etc. [70,79,138,209,237,269]. The possibility of damage means that a lightning protection device may require periodic inspection and/or maintenance that is generally not required for conventional terminals. Although this problem is pointed out [155], there seems to be very little discussion about it in the open literature.

IV. CONCLUSIONS

The possible conclusions that can be drawn from an examination of the literature included in the bibliography are discussed in this section. The main conclusions of this report are briefly summarized in Section VI.

Because of the sparsity of information that can be found in the peer-reviewed literature from tests of early streamer emission air terminals, either in the laboratory or in the natural environment, it is nearly impossible to make quantitatively meaningful statements or judgements about the performance of ESE devices in comparison to conventional Franklin rods. In fact, insufficient reliable quantitative data seem to exist about the performance of conventional rods, and there seems to be an ongoing debate about the best geometrical design for conventional terminals required to achieve optimum lightning attraction efficiency.

Nearly all of the information or data that could found on ESE device performance resulted either from tests performed by manufacturers of lightning protection sys-

tems or by those directly or indirectly employed by such manufacturers. Although abundant criticism is published by non-manufacturers about the performance of ESE devices, especially radioactive air terminals, it is seldom based on actual test data. Those on both sides of the issue invoke lack of evidence in making their case about the performance of ESE terminals. Proponents of these devices claim that a lack of credible statistical data on failure of ESE terminals proves their effectiveness; while critics of these terminals argue that a lack of evidence about the improved performance of ESE terminals over conventional terminals proves their ineffectiveness. In either case, one must beware of faulty logic, in as much as a lack of evidence never proves the lack of something.

There are reports of incidents where ESE devices failed to provide the protection specified by the manufacturer [156,158,165,215]. Statistics on the failure of conventional systems have also been documented [109]. When examining reports of "failures", one can always raise questions about their cause, e.g., whether they are primarily a consequence of exaggerated claims made by the manufacturer or a consequence of misuse (faulty installation) of the device. Reports of isolated failures raise legitimate concerns, but are seldom accompanied by enough supporting data about the event to enable a determination of why the failure occurred. Generally it is difficult to draw significant conclusions from single events that can be used to improve system design or evaluate system performance. There is no reason to believe that an air terminal is 100% efficient in attracting lightning, regardless of what kind of ESE device it uses, if any. Considering the wide range of possible atmospheric conditions and types of lightning behavior that have been recorded, it is not surprising that air terminals of all types will sometimes fail [37,201,271]. Tall structures are reported to be struck occasionally by lightning at points far below the top, i.e., outside of the "protection zone" [173,185,186]. Any claims of 100% efficiency in the performance of a lightning attractor should be viewed with skepticism. In any case, the meaning of the term "efficiency", when specified for an air terminal, should be clearly defined and understood.

A reasonable physical basis for the operation of an ESE device appears to exist in the sense that there is good evidence from laboratory investigations that the probability of initiating a streamer discharge from an electrode can be increased significantly by irradiation or electrical triggering. However, the precise amount by which this enhancement in streamer initiation improves the lightning attraction efficiency of an air terminal remains questionable. There is reason to doubt that it significantly extends the maximum range of protection. A lightning stroke that would not hit a conventional terminal because of the fact that it does not enhance the field at the terminal tip enough to allow streamer formation will also not likely hit a terminal equipped with an ESE device. (The exception would be an ESE device that significantly increases the terminal potential during the approach of a lightning stroke.) In our view, the possible advantage offered by an ESE device, if operated properly, is that it helps to insure that a streamer will be initiated if the field produced by the

oncoming stroke at the terminal becomes sufficiently great to allow streamer propagation. When comparing ESE and conventional terminals, it is probably preferable to consider efficiency rather than zone of protection as a measure of performance.

It is possible that the increase in lightning attraction efficiency gained from using an ESE device can also be achieved by simply using a conventional terminal of greater height [116]. There is no indisputable evidence from the literature that the range of protection offered by a single ESE terminal can be greater than or necessarily the same as the range provided by two or more conventional terminals of the same height with overlapping zones of protection. On the other hand, an array of ESE terminals may provide better protection than a similar array of conventional devices. Although the precise amount by which the ESE device extends or improves the performance of a conventional terminal is generally not known or easily measured, there is no reason to believe that an ESE array will have an inferior performance. We would argue that until issues concerning the relative performances of single ESE and conventional terminals are settled, meaningful statements cannot be made about the comparative performances of arrays of these terminals.

In general, it can be presumed that ESE terminals perform at least as well as conventional terminals with the same geometrical configuration provided, of course, that they are properly designed to avoid significant corona formation during a thunderstorm. In the event that an ESE device fails or becomes inoperative for some reason, the ESE terminal should revert in its characteristics and performance to that of a conventional terminal with the same height, geometrical configuration, and connection to ground.

Although much has been learned about the operation of ESE terminals compared to conventional terminals from laboratory-scale tests which suggest that ESE devices do indeed enhance streamer emission, these results have not, and probably cannot, be used to make quantitative determinations of the relative efficiencies of these terminals for atmospheric conditions under a thunderstorm. At the present time, the results from a limited number of field tests with natural lightning are inconclusive with respect to providing estimates of relative efficiencies. It is not clear that enough data can ever be acquired from such tests to draw quantitative conclusions about attraction efficiency. Tests in the natural environment appear to be most useful in identifying and documenting conditions under which air terminals fail.

Semi-empirical models have recently been developed to calculate striking distances to lightning conductors. These models show promise in providing a method for making realistic estimates of maximum protection range for air terminals. The maximum extent to which ESE devices enhance the attraction efficiency or increase the effective range of protection of a terminal could conceivably be investigated with these models.

V. RECOMMENDATIONS

Until recently, because there is not much that can be done to improve the design of a conventional lightning rod, there was little motivation to perform complicated tests to evaluate the efficiency of these rods as lightning attractors. It has always been recognized that conventional rods sometimes failed and that the reasons for failure were usually attributable to the complex unpredictable nature of the lightning discharge which is almost impossible to understand. With the appearance on the market of competing products (ESE devices that supposedly improve the attraction efficiency of a rod) have come questions about how these new devices work and how they can be tested to verify their performance. Lightning, in the meantime, remains as complicated as ever, and our understanding of lightning seems to progress only very slowly. Given this situation, it is not clear that we can find quantitatively acceptable answers to questions about the performance of lightning protection systems any time soon.

Considering the difficulty of the task, we offer the following recommendations for future work without being specific about realistic time tables and expectations:

1) Give priority to developing new methods for calculating or otherwise determining stiking distances and related zones of protection that are more meaningful from a statistical point of view.

2) Continue and extend laboratory tests to investigate the effects of relevant parameters such as polarity, space charge, wind, and humidity on the streamer initiation probabilities and propagation from ESE and conventional terminals.

3) Continue observations of natural lightning in and around test sites setup with different air terminals in various locations where the frequency of lightning is known to be high.

4) Compile and analyze existing and newly acquired statistical data on the behavior of lightning from different locations and different sources in a central location.

To enhance credibility, more of the testing and data evaluation should, if possible, be performed by individuals or organizations not identified with manufacturers of lightning protection systems.

VI. SUMMARY OF CONCLUSIONS

The main conclusions of this report can be summarized in the following statements:

1) Lightning is a complex, chaotic phenomenon that exhibits a broad range of behavior and characteristics that are predictably unpredictable. Any theory or assessment of lightning protection devices must take this fact into account.

2) A plausible physical basis exists for ESE devices in the sense that they can enhance the probability for initiating an upward propagagating streamer from an air terminal which is directed at an oncoming lightning stroke.

3) Insufficient indisputable information could be found about both ESE and conventional air terminals to allow quantitatively meaningful comparisons to be made about their relative performance in the natural environment.

In conclusion, it could be said that there is yet more to be learned about lightning and about how lightning protection devices work or do not work. The road to better lightning protection is obviously strewn with controversy and it would appear that the path to resolution requires more enlightenment and less thunder.

BIBLIOGRAPHY

SUMMARY OF RATING CRITERIA

(***) - Peer reviewed - directly relevant.

1) archival journal publications.
2) government reports (NTIS).
3) theses.

(**) - Unreviewed - directly relevant.

1) conference papers.
2) reports.
3) preprints.
4) patents.

(**) - Indirectly related.

(*) - Peripherally related.

( ) - Unrated.

1. ( )

TITLE Lightning Technology Roundup

TYPE conference

CONFERENCE International Aerospace and Ground Conference on Lightning and Static Electricity (8th)

LOCATION Fort Worth, TX USA

SPONSOR Federal Aviation Administration Technical Center, Atlantic City, NJ

DATE June 21, 1983

NTIS AD-A169 049/4/XAB

KEYWORD basic; simulation

LANGUAGE English

ABSTRACT This addendum is a compilation of papers presented at the 1983 International Aerospace and Ground Conference on Lightning and Static Electricity, held at the Fort Worth Hilton Hotel, Fort Worth Texas, June 21-23, 1983, but not available for publication in the original conference proceedings. The conference was sponsored by the NICG in concert with the Florida Institute of Technology and in association with the Institute of Electrical and Electronic Engineers, SAE-AE4 committee, the United Kingdom Civil Aviation Authority, Royal Aircraft Establishment, Farnsborough, Culham Laboratory.

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2. (**)

TITLE Electrostatic Protection of the Solar Power Satellite and Rectenna. Part II. Lightning Protection of the Rectenna

TYPE report

SPONSOR National Aeronautics and Space Administration

DATE Nov. 1, 1980

NTIS DE84012301

KEYWORD applications; experimental; Franklin rod; model

LANGUAGE English

ABSTRACT Computer simulations and laboratory tests were used to evaluate the hazard posed by lightning flashes to ground on the SPS rectenna and to make recommendations on a lightning protection system for the rectenna. The distribution of lightning over the lower 48 of the continental United States was determined, as were the interactions of lightning with the rectenna and the modes in which those interactions could damage the rectenna. The studies showed that lightning protection was both required and feasible. Several systems of lightning protection were considered and evaluated. These included two systems that employed lightning rods of different lengths and placed on top of the rectenna's billboards and a third, distributed system. The distributed system is similar to one used by power distribution companies; it consists of short lightning rods all along the length of each billboard that are connected by a horizontal wire above the billboard. The system that not only affords greater protection than the others considered but also offers easiest integration into the rectenna's structural design, is the distributed lightning protection system.

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3. (**)

TITLE Conference Proceedings
TYPE conference
CONFERENCE Lightning and Static Electricity Conference
LOCATION Wright-Patterson AFB, Ohio USA
SPONSOR Air Force Avionics Lab, Wright-Patterson AFB, Ohio
DATE Dec. 1, 1972
NTIS AD-752 551
KEYWORD aircraft; simulation
LANGUAGE English
ABSTRACT The document contains the text of unclassified papers presented at the 1972 Conference on Lightning and Static Electricity, held 12-15 December 1972. The papers document the discussion of the theoretical aspects of both lightning and atmospheric electrification. In addition, the practical control of adverse effects is addressed relative to aerospace vehicles and installations. Sessions include fundamental aspects, missiles and spacecraft, aircraft, advanced composites, fuels, and lightning simulation.

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4. (**)

TITLE Lightning Reference Bibliography 1936-1949
TYPE pamphlet
DATE April 1950
PUBLISHER American Institute of Electrical Engineers, 33 West 39th Street, New York, NY
KEYWORD bibliography; lightning
LANGUAGE English
ABSTRACT COMMENT: This bibliography contains 754 citations of archival and conference papers concerned with different aspects of lightning that were published between 1936 and 1949. Included are many articles relevant to lightning protection and the theory of lightning. It does not appear to contain any articles that are concerned primarily or specifically with ESE devices.

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5. (**)

AUTHORS Abdel-Salam, M.
TITLE Positive Wire-to-Plane Coronas as Influenced by Atmospheric Humidity
TYPE journal
PAGE 35-40
JOURNAL IEEE Transactions on Industry Applications
VOLUME IA-21
NUMBER 1
DATE Jan./Feb. 1985
KEYWORD model; corona; humidity; inception voltage; air
LANGUAGE English
ABSTRACT A method is suggested for calculating the inception voltage and corona current in humid air. It is found that the photoelectron distribution within the ionization layer, which depends upon the gap geometry, plays an important role in deciding whether the

inception voltage increases or decreases with relative humidity. The inception voltage is one of the boundary conditions required in the theoretical analysis of the corona V-I characteristics also presented. The experimental results reported in the literature which differ widely can be explained in light of the present findings.

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6. (***)

AUTHORS Abdel-Salam, M.; El-Mohandes, M. T.; Berger, G.; Senouci, B.
TITLE Onset Criterion of Upward Streamers from a Franklin Rod
TYPE journal
PAGE 45-59
JOURNAL Journal of Electrostatics
VOLUME 24
NUMBER 1
DATE 1989
KEYWORD basic; Franklin rod; model; streamer onset criterion; theoretical
LANGUAGE English
ABSTRACT In this paper the onset criterion of upward streamers from a Franklin rod is formulated as a function of the geometry of the rod and of the height and current of the lightning leader approaching the rod. This leader is approximated by a line and point charge and it is assumed that induced streamers, at the rod, will eventually produce an upward moving leader. The electric field around the rod is calculated using the charge simulation technique. The streamer onset criterion is based on the model proposed by Loeb for self-sustained propagating discharges. For a given rod the upward directed streamers start from the rod at lightning leader heights that depend on the lightning current. The higher this current the higher the location where upward and downward directed leaders meet each other.

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7. (*)

AUTHORS Aihara, Y.; Shindo, T.; Miki, M.; Suzuki, T.
TITLE Laser-Guided Discharge Characteristics of Long Air Gaps and Observation of the Discharge Processes
TYPE journal
PAGE 66-77
JOURNAL Electrical Engineering in Japan
VOLUME 113
NUMBER 4
DATE June 15, 1993
KEYWORD experimental; laser; polarity; rod-rod gap; triggered
LANGUAGE English
ABSTRACT Laser-guided discharge is promising for the protection of power transmission systems against lightning. Several experiments concerning laser-induced electrical discharge have already been performed. However, it is necessary to understand the mechanism of the laser-induced electrical discharge in order to achieve laser-triggered lightning. When a high-power laser beam is focused in air, a high degree of ionization is produced as brilliant beams near the focus. In this paper, an electrical discharge induced up to 2 m

with a high-power CO_2 laser focused by a 10 m focal length mirror is described. Experiments of the laser-guided discharge were carried out by application of an impulse voltage to a rod-rod gap after laser radiation. This paper deals with the effects of delay times and polarity of the impulse voltage on 50 percent flashover voltage characteristics and the observation results of discharge phenomena taken by a still camera, a special camera named ALPS (Automatic Lightning Discharge Progressing Feature Observation System) and an image converter camera.

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8. (**)

AUTHORS Alconchel, O.; Thirion, B.
TITLE Study of a Type of Early Streamer Emission Lightning Conductor
TYPE conference
CONFERENCE Workshop on Physics of Lightning
LOCATION Chamonix, France
DATE Feb. 2, 1993
KEYWORD ESE; description; lightning protection
LANGUAGE French
ABSTRACT COMMENT: A commercial device is described based on generation of an early streamer emission system added to a conventional lightning rod ("Franklin Rod"). Auxiliary electrodes form a gap near the tip of the main rod where a triggered discharge occurs as the stepped leader approaches, thus supplying the charges to initiate a streamer that will close the path before other extraneous projections can generate competing streamers. The energy necessary for the triggered discharge is collected from the (slowly) increasing electric field, while the discharge itself is triggered by a circuit sensitive to the fast rate of increase of the field just as the stepped leader approaches. Results of tests performed in a high voltage laboratory are reported. Details of the circuit design are not given in this report.

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9. (***)

AUTHORS Aleksandrov, G. N.; Berger, G.; Gary, C.
TITLE New Investigations in the Lightning Protection of Substations
TYPE conference
PAGE 23/13-14
CONFERENCE CIGRE
DATE 1994
KEYWORD ESE; Franklin rod; test procedures; experimental
LANGUAGE English
ABSTRACT COMMENTS: This paper reports the results of tests on lightning protection devices performed in two different laboratories. The first series of tests performed at a laboratory in France included comparisons of upward leader initiation time distributions for Franklin and early streamer emission (ESE) lightning rods. The ESE rods show a significantly earlier inception time than the Franklin rods at lower electrical field strengths. The propagating properties of the upward discharge were also investigated and found to be distinctly different for the two types of rods. Details of the ESE method are not given but appear to involve use of a triggering device that creates repetitive high

pulse voltage impulses leading to repetitive high pulse corona discharges. The second series of tests conducted at a laboratory in Russia involves evaluation of statistically reliable tests of lightning protection using single or multiple objects or objects of large area. Tests were performed in the laboratory using 10-15 m spark lengths. Particular attention was given to lightning rods equipped with a toroidal conductor at the top. The dimensions of the lightning protection zones were determined for different geometrical configurations of the lightning rod or rods.

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10. (*)

AUTHORS Allen, N. L.; Dring, D.
TITLE Variation in Corona Formation under Repetitive Impulse Conditions
TYPE conference
PAGE 41.01-
CONFERENCE Fourth International Symposium on High Voltage Engineering
LOCATION Athens, Greece
DATE Sept. 5, 1983
KEYWORD experiment; corona; streamers; impulse breakdown; ion density
LANGUAGE English
ABSTRACT The formation, appearance and properties of positive corona are shown to vary, during impulse testing, depending upon the test procedures adopted. These procedures are shown to affect the ambient negative ion density prior to each impulse: a low ion density tends to result in a "coarse" corona, with clearly visible streamers, and a high ion density, which has been calculated, results in a "fine" corona with appearance similar to a glow. Fine corona is associated with smaller currents extending over a longer time, and with a larger charge deposition, than coarse corona.

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11. (**)

AUTHORS Allibone, T. E.; Meek, J. M.
TITLE The Development of the Spark Discharge
TYPE journal
PAGE 97-126
JOURNAL Proceedings of the Royal Society of London Series A
VOLUME 166
DATE June 16, 1938
KEYWORD experiment; spark discharge; leader velocity; air breakdown; photography
LANGUAGE English
ABSTRACT COMMENT: This work reports on the results from photographic observations of electrical discharge (spark) development under impulse conditions in point-sphere, sphere-point, point-point, and sphere-sphere electrode gaps in air. The sequential photographic records are used to extract estimates of leader velocity. Data are presented for both positive and negative type discharges and factors influencing spark development are discussed. The relevance of the observed spark structure to lightning discharges is also considered. The spark photographs prove the existence of a "pilot" streamer that travels in front of the stepped leader and prepares an ionized path for the subsequent step. This work presents the first observations which clearly showed that a negative discharge is always accompanied by a positive discharge developing from the earthed electrode that meets the leader from the negative discharge in the mid-gap region.

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12. (***)

AUTHORS Allibone, T. E.; Dring, D.

TITLE Influence of Radiation on the Sparkover of Sphere-Plane Gaps Stressed with Impulse Voltages

TYPE journal

PAGE 759-763

JOURNAL Proceedings of the IEE

VOLUME 121

NUMBER 7

DATE July 1974

KEYWORD experiment; radiation effect; impulse breakdown; corona; switching surge

LANGUAGE English

ABSTRACT The influence of gamma radiation and some X radiation on the sparkover of sphere-plane gaps has been studied using spheres of 6.25, 15 and 25 cm diameter, under impulse voltages of both polarities up to 500 kV, and having wave-fronts of 1 to 180 microseconds, all impulses having the same 1000 microsecond wave tail. In general, the use of the 100 mCi gamma-ray source slightly lowers the sparkover voltage V_{50} and fractional probability range for impulses of positive polarity and wavefront duration up to 13 microseconds. With longer wavefronts, radiation increases the sparkover voltage of some gaps. The effects on negative polarity are small. Circuit parameters have been found to have an important influence on some sparkover voltages.

COMMENT: The results of this laboratory investigation using relatively large air gaps equipped with radiation sources appears to be relevant to evaluating the effectiveness of radioactive air terminals used in lightning protection systems. Radiation was found to enhance the discharge initiation probability for steep wave fronts. However, the results of this investigation suggest that radiation sources have a relatively minor and ambiguous effect on electrical discharge initiation in air under impulse conditions.

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13. (**)

AUTHORS Allibone, T. E.; Dring, D.

TITLE Influence of Humidity on the Breakdown of Sphere and Rod Gaps Under Impulse Voltages of Short and Long Wavefronts

TYPE journal

PAGE 1417-1422

JOURNAL IEE Proceedings

VOLUME 119

NUMBER 9

DATE September 1972

KEYWORD experiment; impulse breakdown; humidity effect; air gaps

LANGUAGE English

ABSTRACT Humidity-correction factors have been obtained for the breakdown of a 50 cm sphere gap, rod-rod gap and rod-plane gap using impulse voltages of both polarities up to 500 kV and having waveshapes of 1/50 microseconds, 1/1000 microseconds and 80/1000 microseconds. The correction factor for all waves for the sphere-gap breakdown is 0.3% per g/m^3. The factors for other gaps do not appear to depend much on gaplength over the voltage range 130 kV to 500 kV. Standard deviations of the scatter of results fall with increased spacing to about 2%, with one or two exceptions, and are not dependent on humidity for the range of 4-18.6 g/m^3 investigated.

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14. (**)

AUTHORS Allibone, T. E.; Meek, J. M.
TITLE The Development of the Spark Discharge -II
TYPE journal
PAGE 246-268
JOURNAL Proceedings of the Royal Society of London Series A
VOLUME 169
DATE March 7, 1939
KEYWORD experiment; spark discharge; leader velocity; pressure dependence; photography
LANGUAGE English
ABSTRACT COMMENT: Photographic records are reported of spark breakdown of air under impulse conditions in point-plane gaps. The effect of air pressure on leader velocity was determined. Both positive and negative type discharges were considered and the differences between these two types of discharges are discussed. It was found that even for the longest gap (150 cm) for which records are available, the negative discharge from a point electrode is always met by an ascending positive leader stroke from the earthed plane and the length of this leader is not less than 30% of the gap. In the case of the positive discharge, the positive leader stroke is only infrequently met by an ascending negative leader stroke: the leader stroke of the positive discharge often splits into two main branches as it approaches the earthed plane, but this branching is not necessarily caused by an ascending negative leader.

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15. (**)

AUTHORS Anis, H. I.
TITLE A Study of Early Discharges in Air Gaps
TYPE journal
PAGE 566-574
JOURNAL IEEE Transactions on Industry Applications
VOLUME IA-16
NUMBER 4
DATE July/Aug. 1980
KEYWORD experiment; corona; air breakdown; statistical behavior; delay times; corona onset
LANGUAGE English
ABSTRACT The corona pulses appearing in air gaps under high-voltage impulses are the bases for the complete discharge in these gaps. The various elements affecting the creation of these pulses and their consequent influence on flashover are investigated. The delay of corona pulses and the probability of their occurrence are related to those of breakdown. The results are used to form design grounds for the air insulation of high-voltage apparatus. The experimental work was performed on 50-cm rod-plane air gaps at the High Voltage Laboratory of Cairo University.

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16. (*)

AUTHORS	Arima, I.; Watanabe, T.; Takagi, N.; Kakihara, M.
TITLE	Experimental Study of the Corona Sheath Current in Lightning Return Stroke
TYPE	conference
PAGE	431-434
CONFERENCE	IX International Conference on Gas Discharge and their Applications
LOCATION	Venice, Italy
DATE	Sept. 19, 1988
KEYWORD	basic; corona; experimental
LANGUAGE	English
ABSTRACT	This paper presents the experiment of the corona sheath current initiated by the return stroke. We used the coaxial cylindrical electrode geometry to correspond to the part of the lightning channel. The situation that the return stroke propagates was represented with dropping the potential of the inner electrode to zero.

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17. (***)

AUTHORS	Baatz, H.
TITLE	Radioactive Isotopes Do Not Improve Lightning Protection
TYPE	journal
PAGE	101-104
JOURNAL	Elektrotechnische Zeitschrift ETZ A
VOLUME	93
NUMBER	2
DATE	Feb. 1972
KEYWORD	critique; radioactive rod
LANGUAGE	German
ABSTRACT	An investigation is made into the effect of radioactive irradiation of lightning conductors using breakdown gaps with direct and impulse voltages. As was to be expected from the ratio of the energy of the radiation to the energy of the predischarges, this has no effect on predischarges and breakdown behaviour. In the case of large-area buildings the Faraday cage offers the best lightning protection.

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18. (*)

AUTHORS	Ball, L. M.
TITLE	The Laser Lightning Rod System: Thunderstorm Domestication
TYPE	journal
PAGE	2292-2296
JOURNAL	Applied Optics
VOLUME	13
NUMBER	10
DATE	Oct. 1974
KEYWORD	applications; guided; laser; multiphoton ionization; theoretical
LANGUAGE	English

ABSTRACT An unusual application of the laser, namely protection of life and property from lightning, is described. The device relies on multiphoton ionization in mode-locked beams, rather than on collisional (avalanche) electron production. Feasibility is demonstrated numerically, and relevant principles explained. A method of mobile deployment is mentioned, by which economic (as opposed to scientific) feasibility might be achieved.

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19. (**)

AUTHORS Baral, K. N.; Mackerras, D.
TITLE Positive Cloud-to-Ground Lightning Discharges in Kathmandu Thunderstorms
TYPE journal
PAGE 10331-10340
JOURNAL Journal of Geophysical Research
VOLUME 28
NUMBER D6
DATE June 20, 1993
KEYWORD observations; positive lightning; electric field measurements
LANGUAGE English
ABSTRACT

The occurrence of positive cloud-to-ground lightning discharges in thunderstorms in the vicinity of Kathmandu, Nepal (27.4 degrees N, 85.2 degrees E) has been recorded during the 21 month period from March 1987 to November 1988 inclusive using the daily registrations of a CGR3 lightning flash counter that provided records of the approximate numbers of positive ground flashes, negative ground flashes, and cloud flashes, with effective ranges of about 12 km for cloud flashes, 14 km for negative ground flashes, and 16 km for positive ground flashes. The detection of positive ground flashes was based on the presence of a relatively large negative-going step in the electric field change caused by the positive return stroke in the discharge. It was found that the overall mean proportion of positive ground flashes to all ground flashes was 0.28, and that the overall mean positive ground flash density was 0.6 km^{-2} yr^{-1}. The uncertainty in these values is about ± 50%. The proportions of positive ground flashes in three of the climatic periods in the year were 0.26 in the premonsoon period (February to May inclusive), 0.34 in the monsoon period (June to August inclusive), and 0.38 in the postmonsoon period (September to November inclusive). This apparent increase in the proportion is accompanied by a seasonal decline in electrical activity, the premonsoon period being the most active, and the postmonsoon the least active. The increase also appears to be associated with a decrease in the proportion of cloud flashes to total flashes. The proportion of positive ground flashes is larger than is observed in most low-altitude tropical and subtropical sites but is smaller than that observed in winter thunderstorms at some higher-latitude sites. Possible reasons for the relatively high rate of occurrence of positive ground flashes (unsupported by concurrent atmospheric soundings) are the site altitude, thundercloud charge heights, vertical wind shear and mountainous nature of the terrain.

COMMENT: The results of this paper illustrate the variability in types of lightning strokes with latitude, altitude, and season. At some times and in some parts of the world, positive lightning events represent a significant fraction of all lightning occurrences and therefore cannot be ignored in evaluating the effectiveness of lightning protection systems.

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20. (*)

AUTHORS Barnard, R. W.

TITLE Investigations of Techniques for Reducing Breakdown Voltage in Lightning Arrestor Connectors

TYPE report

DATE July 1977

SPONSOR Energy Research and Development Administration

NTIS SAND-77-0866

KEYWORD experimental; lightning arrestor connector; radioactive rod

LANGUAGE English

ABSTRACT The success of the MC2796 and MC2797 lightning arrestor connectors (LACs) in providing lightning protection for several weapon systems has resulted in requests for other LACs with other protection capabilities. Among these has been the request for lower breakdown voltage. Some of the initial work on techniques for achieving this goal are described. Techniques investigated included modifications to the electrode geometry, the use of rare gas at reduced pressures surrounding the electrodes, and radioactive ionization of the gas. Tests with LACs included controlled electrical breakdown with slow-rising and fast-rising waveforms. From tests at SLA and General Electric Company, an optimum configuration was chosen. The final configuration which achieved 30 to 50 percent lower average breakdown than original LACs, used a modified web and argon gas. This design was implemented in the MC3114 low breakdown voltage LAC.

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21. (**)

AUTHORS Barnes, A. A.

TITLE Predicting Triggered Lightning

TYPE conference

CONFERENCE International Conference on Lightning and Static Electricity

LOCATION Bath, UK

SPONSOR Geophysics Lab (AFSC), Hanscom AFB, MA

DATE Sept. 28, 1989

NTIS AD-A228 621/9/XAB

KEYWORD aircraft; basic; forecasting; rocket; triggered

LANGUAGE English

ABSTRACT The Air Force is concerned about lightning strikes to aircraft and missiles and does not want a repeat of the Atlas-Centaur 67 accident which happened in March 1987. Triggered lightning is caused by the presence of aircraft or missile in an electric field. If the vehicle goes into an area of active natural lightning, then it can be struck by naturally occurring lightning or it can trigger lightning. In either case the result is the same, since the chance of being struck is high, forecasting the possibility of lightning strikes in electrically active regions is easy and fairly accurate. The real problem in forecasting triggered lightning is threefold; one is the forecasting of the development of cumulus clouds which will produce significant electric fields, second is the forecasting of electric fields in clouds which have detached themselves from regions of active charge production, and third is the determination of electrical fields in stratus clouds which straddle the freezing level. The use of low level convergence fields has been shown to be useful in predicting cumulus development over Cape Canaveral, and neural network techniques are being applied to improve these predictions.

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22. (*)

AUTHORS Barnes, A. A.; Berthel, R. O.
TITLE Survey of Laser Lightning Rod Techniques
TYPE conference
CONFERENCE International Conference on Lightning and Static Electricity
LOCATION Cocoa Beach, FL USA
SPONSOR Phillips lab, Hanscom AFB, MA
DATE Aug. 21, 1991
NTIS AD-A239 988/9/XAB
KEYWORD guided; laser; review
LANGUAGE English
ABSTRACT The concept of using a laser to create an ionized path in the atmosphere to act as a lightning rod is not new. Over the past four decades since the invention of the laser, there have been many documented investigations into the ionization of atmospheric gasses with an eye towards creating a laser lightning rod. Initial experimental attempts using lasers operating in the IR were not successful. Although some ionization was attained, it was found that the laser beam was self-quenching so that distances of only tens of meters were obtained in the atmosphere near sea level. This paper briefly reviews the work which has been done in trying to create a laser lightning rod and discusses some ongoing research which has potential for achieving an operational laser lightning rod for use in the protection of missile launch sites, launch vehicles, and other property.

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23. (**)

AUTHORS Beasley, W.
TITLE Positive Cloud-to-Ground Lightning Observations
TYPE journal
PAGE 6131-6138
JOURNAL Journal of Geophysical Research
VOLUME 90
NUMBER D4
DATE June 30, 1985
KEYWORD positive lightning; observations; survey; phenomenology
LANGUAGE English
ABSTRACT Cloud-to-ground lightning discharges have been studied for more than 50 years by means of visual, photographic, and electromagnetic observations as well as direct measurements of current. One of the first questions to be addressed was that of the sign of net effective charge transferred to earth. The conventional wisdom on the subject has been that most cloud-to-ground lightning flashes transfer net negative charge from cloud to ground. There is also evidence that up to one third of the flashes observed in a given study could transfer net positive charge to earth. Both the subject of positive charge transfer to earth in general and the subject of positive return strokes received attention by Workman, Brook, and others in New Mexico occasionally over the last 30 years. Relatively recently, there have been increasingly numerous reports of cloud-to-ground lightning that transfers positive charge to earth in winter thunderstorms in Japan, in summer thunderstorms in Scandinavia, in severe storms in the U.S. Great Plains, in summer thunderstorms in the western United States, in summer thunderstorms in Florida, and in

fall and winter thunderstorms in the northeastern United States. Furthermore, from the most recent observations it is found that positive cloud-to-ground flashes often have return strokes similar to those in negative cloud-to-ground flashes, except for polarity; that most often there is only a single return stroke; and that often a continuing current of large amplitude, or possibly a discharge in the cloud, follows the return stroke.

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24. (***)

AUTHORS Belli, M.; Cremonese, M.; Greco, S.

TITLE Health Implications of the Risks Connected with the Use of Americium 241 for Lightning Protection

TYPE report

DATE Dec. 10, 1975

SPONSOR Istituto Superiore di Sanita, Rome

NTIS N77-12684/5

KEYWORD radiation protection; radioactive rod

LANGUAGE Italian

ABSTRACT Americium metabolism is reviewed together with some information on the biological and pathological effects following americium 241 contamination in order to assess the risk due to the use of radioactive isotopes in lightning conductor installations and the resulting implications on public health. Some aspects of radioprotection are presented and it is concluded that the use of americium 241 for lightning protection exposes the population to undue risks. Summary in English.

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25. (***)

AUTHORS Belli, M.; Salvadori, P.; Sgrilli, E.; Susanna, A.

TITLE Public Health Aspects in the Use of Radium-226 and Americium-241 in Lightning Rods

TYPE report

PAGE 441-447

SPONSOR Nuclear Regulatory Commission-in report "Radioactivity in Consumer Products"

DATE 1978

NTIS PB-288 743/8

KEYWORD radioactive lightning rods; human health; risk/benefit

LANGUAGE English

ABSTRACT COMMENT: In this article the authors express criticism both about the effectiveness and hazards of radioactive air terminals. They conclude with the statement: "From the above considerations the authors conclude that the use of Radium-226 and Americium-241 sources in lightning rods should be considered as a risk not justified by demonstrated benefits."

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26. (**)

AUTHORS	Bent, R. B.
TITLE	Lightning Protection for Buildings, Towers and Personnel
TYPE	conference
CONFERENCE	IEEE Annual Textile Industry Conference 1986
LOCATION	Charlotte, NC USA
SPONSOR	IEEE (avail. from IEEE Service Cent. Cat n 86CH2320-0. Piscataway, NJ USA)
DATE	May 7, 1986
KEYWORD	Franklin rod; radioactive rod; review
LANGUAGE	English
ABSTRACT	The purpose of a lightning rod and the basic requirements for lightning protection for buildings and towers are discussed. Other types of protection such as overhead wires are discussed along with radioactive systems and other dubious elimination schemes. The effects of lightning on persons and animals are also reviewed.

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27. (**)

AUTHORS	Bent, R. B.; Collin, H. L.; Hutchinson, W. C. A.; Chalmers, J. A.
TITLE	Space Charges Produced by Point Discharge From Trees During a Thunderstorm
TYPE	journal
PAGE	67-72
JOURNAL	Journal of Atmospheric and Terrestrial Physics
VOLUME	27
DATE	1965
KEYWORD	space charge; trees; lightning; measurements; corona
LANGUAGE	English
ABSTRACT	Measurements of space charge during a thunderstorm show that this arises from point discharge at trees and confirm that this process must be important in the transfer of electricity between clouds and ground.

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28. (**)

AUTHORS	Berger, G.
TITLE	The Design of a New Approach for Lightning Protection
TYPE	conference
CONFERENCE	National Fire Protection Association Fall Meeting
LOCATION	Phoenix, Arizona USA
DATE	Nov. 14, 1993
KEYWORD	ESE; guided; review
LANGUAGE	English
ABSTRACT	Lightning remains a significant cause of fire around the world, and is especially dangerous to buildings that emit corrosive or highly flammable gases, such as steel, aluminum, or chemical factories. This paper deals with the challenges involved in designing new concepts for lightning protection, taking into account recent advancements in lightning physics and a better understanding of long electrical discharges.

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29. (**)

AUTHORS Berger, G.
TITLE Determination of the Inception Electric Field of the Lightning Upward Leader
TYPE conference
PAGE 225-228
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; Franklin rod; guided; ionizing terminal; model; simulation
LANGUAGE English
ABSTRACT Laboratory experiments have been conducted to investigate the efficiency of Lightning Protection Systems through a representative simulation of the electric field growth due to a negative downward leader propagating towards the ground. After the design of the experiment, we shall compare the development in space and time of the upward discharge issued from various kinds of lightning rod conductors. An accurate determination of the upward leader inception field will be derived and its applications to eventual improvements of the electrogeometric model will be proposed. The lowest inception values are shown to be obtained for lightning rod conductors equipped with a convenient electrical triggering device.

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30. (**)

AUTHORS Berger, G.
TITLE Early Streamer Emission Lightning Rod Conductor
TYPE conference
PAGE 38:1-9
CONFERENCE 1992 International Aerospace and Ground Conference on Lightning and Static Electricity
LOCATION Atlantic City, NJ USA
DATE Oct. 6, 1992
KEYWORD ESE; experimental; Franklin rod; guided; simulation
LANGUAGE English
ABSTRACT Experiments have been performed in high voltage laboratories to simulate the actual conditions of formation and propagation of the upward leader launched from a lightning rod. This testing procedure allows one to investigate the efficiency of any lightning protection system. The conventional Franklin rod has been tested and then compared to an air-terminal using an Early Streamer Emission (ESE) triggering device designed to enhance the protection area of the Franklin rod. Extensive tests have shown that a high voltage pulse ESE air-terminal is more effective than the conventional Franklin rod commonly used in the standards.

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31. (**)

AUTHORS Berger, G.

TITLE Applications of the Electrogeometric Model to Franklin and ESE Lightning Rods

TYPE conference

CONFERENCE Lightning Protection Workshop

LOCATION Hobart Standards, Australia

DATE Nov. 12, 1992

KEYWORD applications; ESE; Franklin rod; guided; model; review

LANGUAGE English

ABSTRACT At the present time, lightning protection design concepts are of geometric nature and more or less associated with electrical considerations. They are not physical enough in spite of considerable international collaborative programs developed in the past such as the works of Les Renardieres Group, or of good theoretical computations such as those of Dellera and Garbagnati. The main design methods, all derived from the same electrogeometrical model, are respectively the use of a cone of protection, the rolling sphere method, the concept of collection volume or the more theoretical probabilistic approach. For the case of lightning rods, they apply to the classical Franklin rod but nothing has been proposed for the Early Streamer Emission (ESE) rods. The aim of this paper is to examine the various methods showing their agreement or disagreement, their practical use according to the main standards and how they may be adapted to fit the experimental data acquired in the field of ESE air terminals.

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32. (**)

AUTHORS Berger, G.

TITLE Formation of the Positive Leader of Long Air Sparks for Various Types of Rod Conductor

TYPE conference

PAGE 43-46

CONFERENCE 22 nd International Conference on Lightning Protection

LOCATION Budapest, Hungary

DATE Sept. 1, 1994

KEYWORD ESE;, laboratory study; Franklin rod; inception times

LANGUAGE English

ABSTRACT Leader initiation field is believed to be independent of the radius of curvature of the positive electrode (critical radius concept). The goal of the present study is to show that it is however possible to act on the continuous leader inception field using additional electrical triggering devices. Investigations on the inception conditions of long positive air sparks launched from a rod conductor have been performed in very large high voltage laboratories for gap lengths up to thirteen meters. Electrical triggering devices have been added to the rod in order to investigate if the continuous leader might be initiated at lower electric fields than those observed on a Franklin rod. Experiments have shown a very effective reduction of the leader inception electric field if compared to the case of the simple rod.

COMMENT: Details of the "electrical triggering devices" are not given in this work, and therefore it is impossible for someone else to replicate these experiments in another laboratory. Validity of the arguments for scaling the laboratory results up to environmental conditions depends on the validity of a theoretical model for leader inception proposed by Rizk.

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33. (*)

AUTHORS Berger, G.; Charrier, J.
TITLE A Simple Model Explaining the Positive Glow Corona in Atmospheric Air
TYPE preprint
CONFERENCE IEEE IAS Conference
LOCATION Mexico City, Mexico
DATE Jan. 1, 1983
KEYWORD basic; experimental; point-plane gap
LANGUAGE English
ABSTRACT A simple model describing the positive glow corona has been formulated on the basis of experimental data. The successive creation and drift of space charge from the anode lead to periodic variations of the electric field at the anode surface. The mean value of this field remains slightly lower than the positive corona inception field. Following each ionization wave, the injected positive charge is sufficient to quench further avalanches before the ionization region is cleared of charge.

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34. (**)

AUTHORS Berger, G.; Goldman, A.; Senouci, B.; Goldman, M.
TITLE Some Basic Ideas to Improve Lightning Interception
TYPE undated preprint
KEYWORD ESE; experimental; guided; sphere-sphere gap
LANGUAGE English
ABSTRACT The only way to improve the lightning interception is to act on the development of the upward tracer. The sequence of events preceding the inception of the ascending leader (corona formation, streamer-to-leader transition) is analyzed on the basis of the physical concepts ruling the development of the electrical discharges in atmospheric air. The faster the sequence, the farther the interception zone. Practical means to enhance each stage of the upward discharge are presented, supported by experimental results. As a consequence, the choice of the most adequate lightning protection system will be guided on the basis of the statements developed in the present paper for any given practical situation.

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35. (**)

AUTHORS Berger, G.; Senouci, B.; Goldman, A.; Goldman, M.
TITLE A Physical Approach for Lightning Protection
TYPE conference
PAGE 435-438
CONFERENCE IX International Conference on Gas Discharge and their Applications
LOCATION Venezia, Italy
DATE Sept. 19, 1988
KEYWORD experimental; ESE; guided; metastables; theoretical
LANGUAGE English
ABSTRACT Means to decrease the stability field for streamer propagation, thus to favor the development of the streamer, are proposed, mainly on the basis of an experiment showing the effect of metastables on the discharge path. The streamer-to-leader transition is discussed. Since this transition occurs from a cold discharge to a hot discharge, the need for a fast impedance transfer in the external circuit is clear.

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36. (**)

AUTHORS Berger, K.

TITLE Measurements and Results of the Lightning Investigation of the Years 1955-1963 on Mount San Salvatore

TYPE journal

PAGE 1-23

JOURNAL Bulletin of the Swiss Elektrotechnischen Vereins

VOLUME 56

NUMBER 1

DATE 1965

KEYWORD observations; lightning; corona current; statistics

LANGUAGE German

ABSTRACT In connection with previous reports, this article describes observations on lightning and oscillographic measurements of lightning currents to the Mount San Salvatore during 1955 to 1963. Furthermore the development of the measuring equipment is mentioned. The frequency of thunderstorm-days is given on different bases. The corona-currents (Saint Elmos fire) into both measuring towers during near lightning storms are discussed and the total electric charge of these currents is calculated. The wave shapes of lightning currents to the towers are discussed on the basis of many examples of oscillograms. The differences in wave shapes of positive and negative lightning currents are shown. Two groups of lightning strokes are distinguished. In the first one, the leader stroke develops upwards, which happens only with metallic towers erected on mountain peaks. The second group of strokes exist also in the flat country; the leader of these strokes develops downwards. The frequency of the different types of strokes is given. The characteristic values of lightning currents, as for example peak value, steepness, electric charge and number of partial strokes and so on are presented in the form of frequency-curves. Finally the importance of these values as a basis for lightning protection is discussed.

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37. (**)

AUTHORS Berger, K.

TITLE Novel Observations on Lightning Discharges: Results of Research on Mount San Salvatore

TYPE journal

PAGE 478-525

JOURNAL Journal of the Franklin Institute

VOLUME 283

NUMBER 6

DATE June 1967

KEYWORD review; observations; photographs; corona; current measurements; lightning strokes

LANGUAGE English

ABSTRACT COMMENT: This paper reviews results of extensive observations of lightning made on Mount San Salvatore hear Lugano, Switzerland. It includes many photographic records of lightning strokes of different types. The following concluding remarks are taken from the paper: "Briefly summarizing some new observations, we mention the following points:

1. On Mount San Salvatore all four forms of lightning strokes appear: both polarities and both directions of progression (downward and upward strokes).

2. Upward and downward strokes can be distinguished by three methods.

a) Fast moving film (Boys-Schonland-Malan Camera).

b) Oscillogram of stroke current: Upward strokes begin with continuing currents of about 100 A during hundredths of a second (leader current); Downward strokes begin with a steep-fronted impulse current (return-stroke current).

c) Observation of branching in the normal lightning photograph with still film. Branching always points in the direction of progression of a leader. The equivalence of these three methods has been proven by comparison.

3. Negative first leaders show very distinct steps. This is true for both downward and upward leaders. Upward leaders from a tower top sometimes even show the very faint corona-envelope at the tip of the leader. The duration of one step is between 29 and 55 microseconds which agrees quite well with Schonland's value of 50 microseconds.

4. Positive leaders have very low luminosity and, in general, have no distinct steps but show rather a periodic variation in light intensity. The duration of two maxima of light intensity is between 40 and 110 microseconds, or twice the value of step formation.

5. Until now we have not succeeded in proving the existence or nonexistence of current pips which would correspond to the steps of upward leaders from a tower.

6. Most interesting is the so-called connecting streamer discharge. Such a discharge is caused by a downward progressing leader. It starts at the tower, contacts the downward leader and therefore initiates the main return stroke by bridging the last remaining gap to earth. With the usual downward negative leader (from a negative cloud) the upward "connecting streamer" (from the positive tower top) is very faint, and generally not longer than a few steps of the downward leader. This agrees with the general observation of item 4. For the comparatively rare downward positive leader (from a positive cloud) the streamer discharge (from the negative tower top) is clearly visible and reaches astonishing lengths of more than 1 km. It then takes the form of a usual negative upward leader. The high luminosity agrees with item 3. The steepness of the current impulse is reduced by these long "connecting streamer discharges."

7. Special streamer discharges may occur which do not reach the lightning channel, but which are produced above the towers by the very pronounced and audible field impulse at the instant of a distant lightning flash. Such incomplete upward discharges may be regarded as secondary strokes that follow a distant primary flash. The question is therefore justified whether all upward strokes could be such secondary strokes."

Not only is the existence of upward propagating streamers verified in this work, but it is also seen that such streamers exhibit significant statistical variability and can be quite different for different polarities of the lightning stroke.

38. (***)

AUTHORS	Berio, G.
TITLE	Use of Ionization in the Air for Lightning Protection
TYPE	journal
PAGE	178-180
JOURNAL	Isotopes and Radiation Technology
VOLUME	8
NUMBER	2
DATE	Winter 1970-1971
KEYWORD	experimental; ionizing rod
LANGUAGE	English
ABSTRACT	The E. F. (electricite froide) lightning rod, which uses eight Am 241 sources to promote the ionization of air is described. This rod has an effective radius of 250 m and is being used extensively in Europe to protect commercial installations from lightning.

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39. (***)

AUTHORS	Besseghini, G.; Zampini, F.
TITLE	Radioprotection in the Installation of Lightning-Rods Equipped with Radioactive Sources
TYPE	journal
PAGE	80-87
JOURNAL	Giornale di Fisica Sanitaria e Protezione Contro le Radiazioni
VOLUME	18
NUMBER	1-2
DATE	January-June 1974
KEYWORD	radiation protection; radioactive rod
LANGUAGE	Italian
ABSTRACT	Administrative and radioprotection problems are discussed. Results are reported of the survey of the level of radioactive contamination on plants with 8 to 10 years half lives in industrial atmospheres. The level of radioactive contamination is acceptably low, but periodical checking is advisable. Assembling as well as dismantling of the equipment should be committed to operators aware of practical principles of radioprotection.

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40. (**)

AUTHORS	Bondiou, A; Gallimberti, I.
TITLE	Theoretical Modelling of the Development of the Positive Spark in Long Gaps
TYPE	journal
PAGE	1252-1266
JOURNAL	Journal of Physics D: Applied Physics
VOLUME	27
DATE	1994
KEYWORD	model; theory; air breakdown; corona; streamers; leader; space charge
LANGUAGE	English
ABSTRACT	The main purpose of this paper is to present a physical model of the positive discharge in long air gaps. A large number of previous experimental and theoretical studies led to the

identification of the different successive phases of the spark development: formation and propagation of first corona streamers, inception of the conductive stem at the electrode tip, formation and development of second corona (or 'leader corona') from the stem, and eventually, the propagation of the leader and leader corona system until the final jump preceding the arc onset. Details of the specific modeling of each phase is presented, using the classical equations for conservation of mass, momentum and energy for each particle species. These basic equations are simplified according to the dominant electrostatic, hydrodynamic or thermodynamic processes involved in each step of the spark development. The resulting models for simulation of the corona and leader phases are coupled with the analytical calculation of the electric field due to the electrodes, the leader channel and the space charge injected into the gap. The different phase simulation models are expressed with a homogeneous simplification level and then linked sequentially into a complete model, which performs the step-by-step simulation of all the successive discharge phases until the final jump. The model described here is self-consistent since only good agreement between computed and experimental results has been obtained in various configurations; the model has been used to simulate the discharge behaviour with perturbations of the applied potential wave and permits the analysis of the conditions for stable propagation of the positive leader. It is shown that some parameters of practical interest, as the 50% breakdown voltage or the time to breakdown can be derived from the proposed model.

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41. (*)

AUTHORS Borisov, M. F.; Zobov, E. A.; Litvinova, I. G.
TITLE Lateral Non-Uniformity in the Glow of a High-Power Spark Channel
TYPE journal
PAGE 66-68
JOURNAL Elektrichestvo
NUMBER 10
DATE Oct. 1991
KEYWORD applications; ball lightning; simulation; theoretical
LANGUAGE Russian
ABSTRACT The results of laboratory simulating a long spark by a controlled sliding discharge have been presented. The authors have found in corners plasma formations ejected into a corner along a bisectrix. To check the surface factor a banded discharge was regenerated in air with the use of an additional electrode. The paper has related the parameters of long-lived plasmoids to the power and convergence angle of shock waves interacting with plasma. A number of conceptions of arising a ball lightning in periphery zone of corona is discussed.

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42. (***)

AUTHORS Bouquegneau, C.
TITLE The Value of Radioactive Lightning Conductors
TYPE journal
PAGE 28-30
JOURNAL Fire Prevention

VOLUME 172
DATE 1984
KEYWORD critique; ionizing terminal; radioactive rod; review
LANGUAGE English
ABSTRACT COMMENTS: Experiments have been carried out in various countries using radioactive sources in lightning conductors. In this article, which first appeared in Revue Belge du Feu, the journal of the Belgian FPA, Professor C. Bouqegneau of Mons Polytechnic looks at the results, to ascertain whether there are any advantages over ordinary non-radioactive conductors. It is argued that there is no convincing experimental or observational evidence which indicates that a radioactive lightning conductor is more advantageous than a non-radioactive conductor of the same geometry.

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43. (**)
AUTHORS Briet, R.
TITLE Theory of Ground-Based Lightning Protection Systems
TYPE preprint
CONFERENCE Evro EM Conference
LOCATION Bordeaux, France
DATE June 1, 1994
KEYWORD lightning protection; theory; model; protection zone
LANGUAGE English
ABSTRACT The Lightning Protection Code in NFPA 78, issued by the National Fire Protection Association in America, indicated that an object is protected if it is completely inside a specified protection zone, which is usually associated with one or more properly grounded lightning rods [MIL-HB-419 can be used as a reference for proper grounding and bonding methods]. However, there is no standard, and no handbook, in which the effectiveness of a lightning protection system is quantified. This paper presents a theory of lightning propagation through contiguous media with different electrical properties, and thus about the interaction of lightning with nearby objects. The theory provides a solid basis for quantifying the effectiveness of conventional lightning protection systems to attract lightning onto itself. This paper is based on a manuscript prepared by, and available from the author.

COMMENT: The paper has been obtained only in a preprint form which does not appear to have been subjected to review.

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44. (*)
AUTHORS Brook, M.
TITLE NOSL (Night/Day Optical Survey of Thunderstorm Lightning) Experiment Support
TYPE report
SPONSOR National Aeronautics and Space Administration
NTIS N87-13140/5/XAB
DATE 1986
KEYWORD basic; experimental; field; simulation
LANGUAGE English

ABSTRACT An optical lightning detector was constructed and flown, along with Vinton cameras and a Fairchild Line Scan Spectrometer, on a U-2 during the summer of 1979. The U-2 lightning data were obtained in daylight, and were supplemented with ground truth taken at Langmuir Laboratory. Simulations were prepared as required to establish experiment operating procedures and science training for the astronauts who would operated the Night/Day Optical Survey of Thunderstorm Lightning (NOSL) equipment during the STS-2 NOSL experiment on the Space Shuttle. Data were analyzed and papers were prepared for publication.

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45. (**)

AUTHORS Brook, M.; Armstrong, G.; Winder, R. P. H.; Vonnegut, B.; Moore, C. B.
TITLE Artificial Initiation of Lightning Discharges
TYPE journal
PAGE 3967-3969
JOURNAL Journal of Geophysical Research
VOLUME 66
NUMBER 11
DATE Nov. 1961
KEYWORD lightning initiation; corona; experiment; wire trigger
LANGUAGE English
ABSTRACT COMMENT: This paper briefly describes laboratory tests that were performed to demonstrate that electrical sparks can be initiated by projecting a fine wire into a spark gap to which a high voltage is applied. On the basis of the simple experiments described, it was concluded that the chances are good for triggering a lightning stroke by projecting a fine wire up under a thundercloud. This is essentially a technique that is now used with rockets to artificially trigger atmospheric lightning stokes. It is argued that use of the rapidly moving wire overcomes the local field reduction due to buildup of space charge from corona which can inhibit discharge initiation.

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46. (*)

AUTHORS Bruce, C. E. R.; Golde, R. H.
TITLE The Lightning Discharge
TYPE journal
PAGE 487-520
JOURNAL The Journal of The Institution of Electrical Engineers Part II
VOLUME 88
NUMBER 6
DATE December 1941
KEYWORD survey; lightning; space charge; statistical distributions; mechanisms
LANGUAGE English
ABSTRACT A survey of the data available indicates that lightning flashes in all thunderstorms have similar characteristics as regards to the times involved and the number of strokes in a flash, and it is shown that Norinder's divergent values are due to misinterpretation of his data. It is suggested that while the charge neutralized in a lightning flash is probably about 50 % greater than hitherto been believed, the cloud potential is only a few per cent of the accepted value, and the energy of a flash about 250 kWh, as compared with

Wilson's value of about 2800 kWh. A theory is advanced bearing on the mechanism of the leader and return strokes, which enables the shape of the lightning current wave to be calculated; in addition, a form is derived for the whole current wave in a multiple flash. A synthesis made from the results of many investigations leads to a picture of the mechanism of the return stroke and to the calculation of the various field changes produced, which agree well with those observed both in shape and in amplitude. New light is thrown on the analysis of the electrostatic field change caused by a stroke. The importance of space charge is emphasized in several connections, including the neutralization of cloud charge thereby, the frequency of "air discharges" and the peculiarity of flashes to the Empire State Building, the currents to which have been re-analyzed. The effect of direct strokes to transmission lines is investigated, and is shown that successive strokes which do not cause flashover are unlikely. The polarity of flashes to earth is shown to differ in tropical and temperate regions, and it is concluded that the polarity of stokes to phase wires cannot be deduced from that of strokes to towers. Suggestions are made as to further investigations.

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47. (**)

AUTHORS Burrows, B. J. C.
TITLE Review of Alternative Systems
TYPE conference
PAGE 3.3/1-7
CONFERENCE Lightning Protection Seminar Proceedings
LOCATION Leatherhead, UK
SPONSOR ERA Technology
DATE Dec. 1, 1987
KEYWORD critique; coaxial downleads; dissipation array; radioactive rod
LANGUAGE English
ABSTRACT The author comments on the performance of alternative lightning protection systems, that is, alternative to the ones recommended in the various national standards including BS 6651. The alternatives which will be commented on are: radioactive lightning air terminations; other forms of patented air terminations (nonradioactive); strike prevention devices; and screened (or so-called coaxial) downleads. Of these, serious consideration has to be given only to some forms of strike protection devices such as dissipation arrays where there is reliable evidence. Most of the others suffer from a lack of credible evidence, either laboratory or from in-service use.

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48. (**)

AUTHORS Burrows, B. J. C.
TITLE The Franklin Rod - An Update
TYPE conference
PAGE 41-46
CONFERENCE IEE Conference Publication no. 236
SPONSOR Institution of Electrical Engineers, UK
DATE 1984
KEYWORD review; lightning rod; protection zone; ionizing radiation; corona

LANGUAGE English

ABSTRACT This paper reviews recent developments and claims about lightning protection that are based on or are extensions of the 'Franklin rod'. Perhaps the most important recent development in the lightning protection of buildings etc. is the work on the rolling sphere method which Horvath's paper works up into a comprehensive statistical approach to lightning strike probability [T. Horvath, "Application of the lightning sphere method in the Hugarian Standard for lightning protection", 16th International Conference on Lightning Protection, Szeged, 1981, paper R-4.03]. Apart from this, the most important development in lightning protection of systems is a better understanding of the mechanisms of interference and improved techniques for screening, bonding and earthing to keep lightning currents out of modern telecommunications and data processing equipment. Also, better surge suppressors are now available. Finally, it is unfortunate that claims are made for apparatus having doubtful value and which do not satisfy fundamental electro-magnetic principles. It is sad that devices such as radioactive air terminations and the so-called 'coax' down leads are heavily promoted since the weight of evidence against the use of these devices is very great.

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49. (**)

AUTHORS Butstein, S.; Mariana, E.

TITLE Active and Passive Lightning Protection

TYPE journal

PAGE 143-152

JOURNAL Revista Electrotecnica

VOLUME 76

NUMBER 5

DATE Sept.-Oct. 1990

KEYWORD Franklin rod; ionizing terminal; radioactive rod; review

LANGUAGE Spanish

ABSTRACT The authors begin with some generalities concerning the history of knowledge of lightning and of lightning protection, leading up to a discussion of the possibility of influencing the course of the lightning stroke by ionizing the air by an electrical discharge from points or by disposition of radioactive material. They then deal with the physics and electrical characteristics of lightning and with some aspects of lightning research. They describe the Franklin lightning conductor and work on radioactive conductors. The section concludes with an account of a novel device in which the piezoelectric effect is used to generate a copious supply of ions which are so directed as to influence the course of the stroke.

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50. (*)

AUTHORS Carpenter, Roy B.

TITLE Lightning Prevention -- Practical and Proven

TYPE journal

PAGE 90-96

JOURNAL Measurements & Data

NUMBER 1

DATE	1976
KEYWORD	dissipation array; review
LANGUAGE	English
ABSTRACT	Presents a review of lightning phenomena and available protection systems. Presents and justifies dissipation array system.

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51. (**)

AUTHORS	Carrara, G.; Thione, L.
TITLE	Switching Surge Strength of Large Air Gaps: A Physical Approach
TYPE	journal
PAGE	512-524
JOURNAL	IEEE Transactions on Power Apparatus and Systems
VOLUME	PAS-95
NUMBER	2
DATE	Mar./Apr. 1976
KEYWORD	air breakdown; switching surges; measurement; corona inception; leader inception
LANGUAGE	English
ABSTRACT	A method is introduced for the determination of the sparkover voltage of practically any configuration subjected to switching impulses of any polarity, applied to one or more electrodes, when the discharge process is governed by the phenomena occurring at a positively charged electrode. The method is applied to some configurations, especially chosen to show its important features, and the results obtained are compared with actual test results. It is finally shown which are the directions in which the studies on the discharge phenomenon could improve the precision and the applicability of the method.

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52. (*)

AUTHORS	Carrus, A.
TITLE	An Inductance on the Marx Generator Tail Branch-New Technique for High Efficiency Laboratory Reproduction of Short Time to Half Value Lightning Impulses
TYPE	journal
PAGE	90-94
JOURNAL	IEEE Transactions on Power Delivery
VOLUME	4
NUMBER	1
DATE	Jan. 1989
KEYWORD	experimental; simulation
LANGUAGE	English
ABSTRACT	A technique is presented for the generation of short-tailed lightning impulses with an acceptable degree of efficiency for use in power system protection studies. The method consists of connecting an in-air inductance in series with the tail resistance in one of the standard configurations of the Marx circuit. The validity of the solution has been ascertained experimentally, and a criterion is provided for the analytical determination of the most suitable value of this parameter.

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53. (***)

AUTHORS Cassie, A. M.

TITLE The Effect of a Radioactive Source on the Path of a Lightning Stroke

TYPE report

SPONSOR Electrical Research Association, Surrey, UK

DATE 1969

KEYWORD critique; radioactive rod

LANGUAGE English

ABSTRACT The field equations for a medium of non-uniform electrical conductivity are discussed in relation to their possible influence on the path of a lightning leader stroke. The conductivity due to a cone of radiation from a typical powerful radio-therapeutic source is calculated from which the numerical values indicate that the dynamic properties for the field predominate. This leads to the conclusion that even such a source can have only negligible influence on the path of the leader stroke while the sources used commercially for lightning protection are totally incapable of producing any effect whatsoever.

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54. (*)

AUTHORS Caylor, I. J.; Chandrasekar, V.; Bringi, V. N.; Minger, S. S.

TITLE Multiparameter Radar Observations of Lightning

TYPE conference

PAGE 306-308

CONFERENCE International Conference on Radar Meteorology 1993

LOCATION Norman, OK USA

SPONSOR American Meteorological Society

DATE 1993

KEYWORD applications; basic; experimental; field; plasma channel; temperature

LANGUAGE English

ABSTRACT Observations of lightning were made in central Florida during the 1991 Convective and Precipitation/ Electrification experiment (CaPE) with the NCAR CP-2 multiparameter radar. The CaPE observations presented are unique in that they were made simultaneously at S- and X-band wavelengths with dual linear polarization. One of the questions concerning the radar observation of lightning deals with the temperature of the plasma channel. Most recently Holmes et. al. (1980) have interpreted their data in terms of a low temperature (underdense) plasma while Williams et. al. (1989) have supported the theory of a hot (overdense) plasma. An overdense plasma is a highly conducting target at conventional radar wavelengths and difficulty in detecting lightning at short wavelengths is explained by masking of the lightning by the precipitation echo. The data presented address this question and the additional polarimetric information provides insight into the spatial geometry of the lightning echo.

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55. (**)

AUTHORS	Chalmers, J. A.
TITLE	Point-discharge Currents Through a Living Tree During a Thunderstorm
TYPE	journal
PAGE	1059-1063
JOURNAL	Journal of Atmospheric and Terrestrial Physics
VOLUME	24
PUBLISHER	Pergamon Press Ltd.
DATE	1962
KEYWORD	corona; trees; thunderstorm
LANGUAGE	English
ABSTRACT	Currents down a living tree during a thunderstorm show effects different from those down a metal point. The results could be explained if the tree behaves as a resistance-capacitance element of time constant about 90 seconds.

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56. (***)

AUTHORS	Chalmers, J. A.
TITLE	Point Discharge Currents
TYPE	journal
PAGE	301-305
JOURNAL	Journal of Atmospheric and Terrestrial Physics
VOLUME	2
DATE	1951
KEYWORD	theory; corona; lightning; lightning conductor
LANGUAGE	English
ABSTRACT	It is shown theoretically that the total point discharge current below a cloud is nearly independent of the nature of the points, so that point discharge currents significant in the maintenance of the earth's charge are not confined to forest and mountain areas. It is also shown that a lightning conductor will have practically no influence upon the probability of a lightning flash occurring.

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57. (**)

AUTHORS	Cheng, J. S.
TITLE	RC Circuit Model of Lightning Beams on a Very Tall Structure
TYPE	conference
PAGE	183-193
CONFERENCE	Electromagnetic Compatibility 1984, Seventh International Warsaw Symposium
LOCATION	Warsaw, Poland
SPONSOR	Warsaw Technical University (Warsaw, Poland)
DATE	June 18, 1984
KEYWORD	model; tall structures; theoretical; upward leader
LANGUAGE	English
ABSTRACT	An RC circuit model has been developed to predict the effect of tall structures on the lightning characteristics. The results show that the total charge in a downward lightning

flash and the percentage of the upward leader from tall structures are predicted to increase with increasing structure heights, and this prediction agrees well with the recent lightning observations.

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58. (***)

AUTHORS Chew, T. P.
TITLE Some Aspects of the Lightning Protection Mechanism and Radioactive Lightning Rods
TYPE journal
PAGE 58-67
JOURNAL Journal of the Institution of Engineers, Malaysia
VOLUME 31
DATE June-Dec 1982
KEYWORD practical; radioactive lightning rod
LANGUAGE English
ABSTRACT This paper presents recent developments in the mechanism of lightning protection and discusses the theoretical and experimental aspects on the use of radioactive lightning rods. On the mechanism of lightning protection, the effect of electrical field distortion caused by a tall structure is examined with respect to the early formation of the upward streamer. The results of dynamic modeling of the initial stages of the lightning protection mechanism are presented.

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59. (***)

AUTHORS Chew, T. P.
TITLE The Mechanism of Lightning Protection
TYPE thesis
DATE September 1979
PUBLISHER Faculty of Engineering, University of Malaya
KEYWORD lightning protection; radioactive lightning rod; analysis; measurements
LANGUAGE English
ABSTRACT This thesis is concerned with the study of the mechanism of lightning protection. The main interest lies in the study of the performance of a radioactive lightning rod as compared with that of a conventional Franklin rod. In addition, a study on striking distance determination is made.

In Chapter 1, a review of relevant literature is made. The attractive effect of a lightning conductor is discussed. The controversy over the effectiveness of radioactive lightning rod as a protective device with a wider range of coverage compared with an ordinary Franklin rod is presented and discussed.

Chapter 2 describes a recording and retrieval system designed to measure point discharge currents from a radioactive rod and a Franklin rod that are mounted separately on two 110-foot (30.5 meter) towers. A coaxial current shunt has been installed to measure direct stroke current in case of a lightning strike to a Franklin rod. Comparison with other existing systems shows that the present system has the advantage of retrieving

recorded data on magnetic tape at a later date. It also allows the adjustment of the retrieved output to any required resolution without the fear of losing vital information.

In Chapter 3, the results of the data collected using the recording system are analyzed and their implications to the lightning protection mechanism are discussed. Three types of discharge patterns could be distinguished. It is found that in steady electric fields the point discharge currents emitted by the radioactive lightning rod are smaller than those emitted by the Franklin rod. However, under impulse electric fields, the impulse currents flowing in the radioactive rods are larger. This indicates that the rate of streamer growth under impulse conditions is faster on the radioactive rod.

To carry out a study on striking distance, an improved method of calculating electrostatic fields near complicated electrode configurations is described in Chapter 4. The method of charge simulation is used to determine the surface charge density on an object. The factors affecting the accuracy of the simulation are discussed. Comparison with other methods shows the higher accuracy that can be achieved by this method.

Chapter 5 describes the development of the computer program used for the study of striking distance determination. The method described in Chapter 4 is used for calculation of electrostatic fields near a lightning rod. The basic physical processes of electrical discharge are applied to the study of the lightning protection mechanism by modeling the corona onset-corona streamer propagation at the lightning rod tip. The effects of certain criteria on the attractive effect of the lightning and hence, the striking distance are studied. The effect of structure height is also discussed.

Chapter 6 concludes the thesis by highlighting the major findings of this research. Suggestions for further work are also made.

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60. (*)

AUTHORS	Clifford, D. W.; Crouch, K. E.; Schulte, E. H.
TITLE	Lightning Simulation and Testing
TYPE	journal
PAGE	209-224
JOURNAL	IEEE Transactions on Electromagnetic Compatibility
NUMBER	2
DATE	May 1982
KEYWORD	aircraft; practical; review; simulation
LANGUAGE	English
ABSTRACT	Laboratory simulation testing is relied upon for assessing the effects of lightning on aircraft and other aerospace systems. This paper reviews the laboratory equipment, techniques, and test waveforms used in simulating the important effects of atmospheric electricity on aerospace systems. Test criteria and techniques are well established for simulating the direct physical damage effects of lightning, but tests for determining the indirect, induced-coupling effects of lightning are still in the development stage. These last tests are necessary for evaluating the effects of the lightning environment on modern aircraft which make extensive use of computerized flight-control systems.

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61. (**)

AUTHORS Cooray, V.; Perez, H.
TITLE Some Features of Lightning Flashes Observed in Sweden
TYPE journal
PAGE 10683-10688
JOURNAL Journal of Geophysical Research
VOLUME 99
NUMBER D5
DATE May 20, 1994
KEYWORD survey; interstroke intervals; statistical distributions; lightning flashes
LANGUAGE English
ABSTRACT Characteristics of lightning flashes in Sweden were measured by recording the electric fields generated by the whole flash in microsecond resolution. The results were gathered from five thunderstorms occurring within 50-100 km from the measuring site. For negative ground flashes the geometric and arithmetic mean of the interstroke intervals were 48 ms and 65 ms, respectively. The corresponding values for the positive ground flashes were 64 ms and 92 ms, respectively. It was found that about 24% of the negative multiple-stroke ground flashes had at least one subsequent stroke with a peak electric field larger than that of the first return stroke. Furthermore, about 15% of the subsequent strokes had peak electric field amplitudes larger than those of the first return strokes. The geometric mean of the ratio of the subsequent stroke peak field to the first return stroke peak field was 0.5. The mean number of strokes per flash was 3.4 and 18% of the flashes were single-stroke flashes.

COMMENT: This work clearly demonstrates that lightning is a phenomenon which exhibits significant statistical variability. It points to the difficulties to be encountered in any attempt to define a "standard" lightning stroke.

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62. (***)

AUTHORS Corvino, A.
TITLE Lightning Protection for Building Structures
TYPE journal
PAGE 493-501
JOURNAL Elettrificazione
NUMBER 11
DATE Nov. 1982
KEYWORD critique; radioactive rod; review
LANGUAGE Italian
ABSTRACT Presents the (Italian) isokeraunic statistics for 1979 and summarises the (Italian) regulations for lightning protection. Reviews alternative arrangements of lightning arresters and concludes that the field performance of devices using radioactive isotopes does not match the laboratory predictions. Includes details of earth conductors and their effects on voltages developed during lightning discharges.

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63. (**)

AUTHORS Dawson, G. A.; Winn, W. P.

TITLE A Model for Streamer Propagation

TYPE journal

PAGE 159-171

JOURNAL Zeitschrift fur Physik

VOLUME 183

DATE 1965

KEYWORD streamer; model; propagation criterion

LANGUAGE English

ABSTRACT A model is presented to describe the propagation of positive corona streamers in the low field region of a non-uniform field gap in atmospheric air. It has been assumed that the growth is a property solely of the streamer tip, uninfluenced by the channel conductivity. Calculations from the model indicate that the criterion for propagation of a streamer in zero external field is that the number of ions in the tip be 10^8 and the radius about 0.003 cm. It is proposed that the streamer ceases to propagate as a result of the loss of energy of the tip due to the formation of ion pairs in the channel. The results of previous experimental observations of streamers are compared with calculations derived from the model and a prediction from the model of the lifetime of streamers after voltage removal is discussed.

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64. (***)

AUTHORS Dellara, L.; Garbagnati, E.

TITLE Lightning Stroke Simulation by Means of the Leader Progression Model. Part I: Description of the Model and Evaluation of Exposure of Free-Standing Structures

TYPE journal

PAGE 2009-2017

JOURNAL IEEE Transactions on Power Delivery

VOLUME 5

NUMBER 4

DATE 1990

KEYWORD basic; critical radius; field; model; theoretical

LANGUAGE English

ABSTRACT A model of lightning channel progression towards the earth is given based on the up to date knowledge on the physics of discharge in long air gaps. The physical assessment of the electric field is done with the charge simulation method which is adopted to describe using a computer program all parameters involved in the progression of the negative downward channels towards the earth and in the inception and propagation of upward positive channels from earthed structures. Reference is made to the critical radius concept acquired with laboratory tests with long front surges. A check of the model with field data relevant to free-standing structures is presented and a reasonable agreement is found.

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65. (**)

AUTHORS Dellera, L.; Garbagnati, E.
TITLE Overhead Power Line Lightning Protection
TYPE report
SPONSOR Ente Nazionale per l'Energia Elettrica, Milan (Italy)
NTIS DE92705849/XAB
DATE 1990
KEYWORD basic; experimental; model; simulation; simulation evaluation
LANGUAGE Italian
ABSTRACT This paper presents a mathematical model, developed by ENEL (The Italian National Electricity Board) in collaboration with the CESI (Italy) labs, to simulate lightning bolt behaviour. The initial assumption is that there exists a substantial similarity between natural phenomena governing the triggering and progression in space of lightning and those giving rise to 30 meter long disruptive discharges obtained during the course of lab tests involving 300-1000 μs peak time impulses. The paper demonstrates how the model is able to analytically simulate the propagation of a bolt descending towards a target structure; impact; the formation of counter discharges deriving from the target's critical structural element; the propagation of the counter discharge up to eventual interception with the descending bolt.

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66. (**)

AUTHORS Dellera, L.; Garbagnati, E.
TITLE Shielding Failure Evaluation: Application of the Leader Progression Model
TYPE conference
PAGE 31-36
CONFERENCE International Conference on Lightning and Power Systems
LOCATION London, England
SPONSOR IEE of London, England and New York, NY
DATE June 5, 1984
KEYWORD model; simulation; simulation evaluation
LANGUAGE English
ABSTRACT Up to now, the design of the lightning protection of structures has been faced using the empirical approach based on the 'striking distance' concept. The following new approach, recently developed, is proposed based on the latest knowledge of the physics of the discharge. The approach is based on the idea that a substantial similarity exists between the lightning phenomena and the discharge in large air gaps.

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67. (***)

AUTHORS Dellera, L.; Garbagnati, E.; Pomponi, R.; Ronchetti, P.; Solbiati, G.; Lo Piparo, G.
TITLE Lightning Protection of Structures. Part I: Lightning Protective Systems: Air Terminations
TYPE journal
PAGE 185-195
JOURNAL Energia Elettrica

VOLUME	61
NUMBER	5
DATE	May 1984
KEYWORD	basic; review; shielding; theoretical; upward leader
LANGUAGE	English
ABSTRACT	A short review of theories relevant to the final part of the propagation of lightning flashes is presented. The most recent knowledge on physics of discharge derived from researches on long air gap sparks is considered to assess the conditions for the inception of upward leaders from earthed structures. Shielding criteria are then defined which take into account the risk of damage of the protected structure related with the statistical distributions of the lightning parameters involved in the phenomenon. Spacing between air termination and protected structure to withstand induced voltage stress is examined. Thermal effects at the impact point are summarized and practical sizing of air-termination elements is given.

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68. (**)

AUTHORS	Dertz, W.; Fritsch, V.
TITLE	Determination of Areas of Transmission Towers Attracting Lightning Strokes
TYPE	journal
PAGE	389-394
JOURNAL	Elektrizitaetswirtschaft
VOLUME	68
NUMBER	12
DATE	June 9, 1969
KEYWORD	model; streamer formation; theoretical
LANGUAGE	German
ABSTRACT	Protective measures are required to prevent lightning damage to h-v overhead lines; on basis of results of modern lightning research, attempt is made to divide different types of lightning discharge into groups; of special importance for classification under range of protection of collecting device, is formation of streamer; by using model tests, attempt is made to show formation of streamer discharges with impulse voltage of about 3 MV on different types of overhead line towers.

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69. (**)

AUTHORS	Dhali, S. K.; Williams, P. F.
TITLE	Two-dimensional Studies of Streamers in Gases
TYPE	journal
PAGE	4696-4707
JOURNAL	Journal of Applied Physics
VOLUME	62
NUMBER	12
DATE	Dec. 15, 1987
KEYWORD	streamers; model
LANGUAGE	English

ABSTRACT We present the results of two-dimensional computer simulations of streamer initiation and propagation in atmospheric pressure nitrogen. The simulation algorithm makes use of flux-corrected transport techniques and was used as a tool to study the solutions of the transport equations under conditions suitable for streamers, for which realistic analytical solutions are not known. We present and discuss conclusions about streamer transport based on the results of these studies. Finally, we present a novel method of checking on the numerical accuracy with which the algorithm solves the transport equations.

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70. (*)

AUTHORS Dobbing, J. A.; Hanson, A. W.; Little, P. F.
TITLE Simulated Lightning Attachments to Aircraft Skins
TYPE conference
PAGE 289-292
CONFERENCE 5th International Conference on Gas Discharges
LOCATION Liverpool, UK
DATE Sept. 11, 1978
KEYWORD aircraft; experimental; simulation
LANGUAGE English
ABSTRACT On average every civil aircraft is struck by lightning once per year. Normally this results in a surface pitting, though occasionally the arc is of sufficient intensity to puncture the skin. This could have serious consequences if an integral fuel tank were involved. 2 mm thick aluminum alloy skins provide acceptable resistance to puncture. With the availability of modern high strength alloys there is a trend towards the use of much thinner skins, which are clearly more likely to be punctured by a lightning arc. In order to study the puncture of metal skins in the laboratory it is necessary to produce arcs whose current and duration are similar to natural lightning. Since melting at an arc root is a relatively slow process it is only necessary to study arcs which persist for times greater than about 1 ms. Lightning current pulses which fall in this category have an amplitude of 100 A - 5 kA and duration up to 200 ms at low currents and 5 ms at high currents.

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71. (**)

AUTHORS Domens, P.; Gilbert, A.; Dupuy, J.; Hutzler, B.
TITLE Propagation of the Positive Streamer-Leader in a 16.7m Rod-Plane Gap
TYPE journal
PAGE 1748-1757
JOURNAL Journal of Physics D: Applied Physics
VOLUME 24
DATE 1991
KEYWORD streamers; leaders; experiment; positive switching impulse
LANGUAGE English
ABSTRACT Experimental results concerning the propagation of a spark in a 16.7 m rod-plane gap are presented. Positive switching impulses are used. The parameters of the discharge are measured and the trajectory of the leader-leader corona system is studied as a function of time (withstand and breakdown events). Three main types of propagation are found: continuous, oscillatory and restrike. For each type, the propagation mechanisms of the leader-leader corona system are discussed from a physical point of view.

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72. (***)

AUTHORS	Dragan, G.; Ungureanu, M.
TITLE	The Striking Distance of Lightning
TYPE	journal
PAGE	191-197
JOURNAL	Revue Roumaine des Sciences Techniques, Serie Electrotechnique et Energetique
VOLUME	27
NUMBER	2
DATE	April-June 1982
KEYWORD	basic; streamer; theoretical
LANGUAGE	English
ABSTRACT	The charge induced in the lightning arrester rod is determined for a certain shape of the electric charges around the leader channel and considering their position versus a lightning arrester. The electric field intensity at the lightning arrester top is given by the electric field of the space charges of the leader approaching the earth and by the electric charges induced. The moment this field intensity surpasses a critical value (26 kV/cm), the development of the streamer towards the leader begins and this corresponds to the striking distance. The paper presents the analytical relations as well as the calculation results for the actually considered cases.

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73. (**)

AUTHORS	Dupuy, J.
TITLE	Negative Discharge in Air
TYPE	conference
PAGE	19-24
CONFERENCE	Proceedings of the 4th Japan-France Workshop on Lightning
LOCATION	Kanazawa, Japan
DATE	Nov. 11, 1991
KEYWORD	basic; experimental; rod-plane gap
LANGUAGE	English
ABSTRACT	Negative discharge in air was investigated during several test periods in "Les Renardieres" H. V. laboratory. Switching impulses have been applied to rod to plane gaps. Gap spacing values were 5, 7 m and 16.7 m. Some results about 16.7 m gap spacing are presented and discussed in relation to lightning phenomena.

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74. (**)

AUTHORS	Dyakonov, M. I.; Kachorovskii, V. Y.
TITLE	Streamer Discharge in a Homogeneous Field
TYPE	journal
PAGE	1070-1074
JOURNAL	Soviet Physics JETP
VOLUME	68
NUMBER	5

DATE May, 1989
PUBLISHER American Institute of Physics
KEYWORD streamer; model; homogeneous field
LANGUAGE English
ABSTRACT A very simple model of the propagation of a streamer in a homogeneous electric field is qualitatively investigated. It is shown that there exists a critical field at which stationary (with constant velocity and head radius) streamer motion is possible. In a field stronger (weaker) than critical, the head radius and the propagation velocity should increase (decrease) with time. The theoretical estimates obtained for the streamer parameters agree well with recently published numerical calculations.

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75. (***)
AUTHORS Eriksson, A. J.
TITLE The Incidence of Lightning Strikes to Power Lines
TYPE journal
PAGE 859-870
JOURNAL IEEE Tansactions on Power Delivery
VOLUME PWRD-2
NUMBER 3
DATE July 1987
KEYWORD model; lightning strike; power line; survey; attractive radius concept
LANGUAGE English
ABSTRACT This paper addresses the lightning attractive radius concept and procedures for estimating the number of lightning flashes to power lines. Empirical data - drawn from extensive observations of lightning incidence upon various practical structures (including lines) - are related to a simple analytical model of the striking process, and a generalized expression for estimating strike incidence is presented. Comparison of the new expression with current practice, suggests that the latter may lead to underestimations of more than 50% in the height range 10 - 30 m, and additionally, that expected strike incidence to taller structures could be overestimated by 30% or more.

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76. (**)
AUTHORS Eybert-Berard, A.; Thirion, B.; Berlandis, J. P.; Bador, B.; Gary, C.
TITLE In situ Lightning Rod Tests and Analysis
TYPE conference
CONFERENCE Lightning and Mountains
LOCATION Chamonix Mont-Blanc, France
SPONSOR Societe des Electricians et Electroniciers et Club Alpin Francais
DATE June 6, 1994
KEYWORD tests; ESE lightning rod; triggered lightning
LANGUAGE English
ABSTRACT In the context of the latest triggered lightning test program in Florida, a French lightning rod company entrusted a series of experimental studies with both natural and triggered lightning to CEA Grenoble (CEA is a very well known governmental research institute in

France). Three different commercial lightning rods were used and compared to a simple air terminal. The results presented here enable us to draw encouraging conclusions.

COMMENT: This appears to be primarily an interim report that is focused on describing procedures and facilities that are being developed and tested for use in planned field tests of different air terminal types at the Camp Blanding Rocket Triggered Lightning Test Facility in Florida. No significant results concerning the relative performance or effectiveness of different types of lightning protection devices, e.g., ESE versus conventional terminals, are presented in the written report.

NOTE: The original abstract identified a manufacturer by name which has been deleted.

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77. (*)

AUTHORS Farish, O.
TITLE Acting on Impulse: Applications of HV Pulse Technology
TYPE journal
PAGE 277-286
JOURNAL Engineering Science and Educational Journal
DATE December 1994
KEYWORD review; impulse testing; laboratory methods; simulation
LANGUAGE English
ABSTRACT High-voltage pulse technology began in the 18th century with the first attempts to simulate lightning. From the 1890's to the 1970's its importance in industrialized countries was concerned mainly with the development of HV and EHV transmission systems. The last two decades, however, have seen explosive growth of new applications in the aerospace, energy, defense, manufacturing and process industries. The paper describes the switching and pulse-forming techniques used to achieve features such as ultrafast risetime and high peak power, and reviews the use of HV pulse technology in a wide range of applications including fusion reactors, lasers, mineral extraction and processing, high-speed imaging and pollution control systems.

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78. (***)

AUTHORS Fieux, R. P.; Gary, C. H.; Hutzler, B. P.; Eybert-Berard, A. R.; Hubert, P. L.; Meesters, A. C.; Perroud, P. H.; Hamelin, J. H.; Person, J. M.
TITLE Research on Artificially Triggered Lightning in France
TYPE journal
PAGE 725-733
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS-97
NUMBER 3
DATE May/June, 1978
KEYWORD research facility; triggered lightning; rocket; photographs
LANGUAGE English
ABSTRACT An experimental station for research on lightning and lightning effects was built in the Massif Central (France) in 1973. The experimental procedure is an application of

artificial triggering of lightning flashes by means of the wire and rocket technique, which has previously been shown to be valid by M. M. Newman.

The station is briefly described and the triggering procedure is explained.

The physical and electrical characteristics of triggered lightning flashes are analyzed. Their properties are compared with those of natural lightning flashes. Some applications are reviewed.

COMMENT: Among the statements made in the conclusion of this work, the following are particularly relevant to the use of triggered lightning to test the performance of lightning rods:

"Peak values of currents recorded until now are, on the average, lower than those which have been registered during other experiments on natural lightning. The characteristics observed are much nearer to those of subsequent strokes of natural lightning but we observed a majority of impulses having rise times less than 0.5 microseconds."

"The characteristics of the triggered lightning strokes enables numerous applications to be considered in the field of electrical engineering research. However, this method cannot be applied to the problems related to the properties of the first stroke (i.e. striking distance)."

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79. (*)

AUTHORS Fisher, R. J.; Uman, M. A.

TITLE Simulation Fidelity in Lightning Penetration Studies

TYPE report

SPONSOR Department of Energy

DATE Feb. 1, 1990

NTIS DE90006367/XAB

KEYWORD review; simulation; simulation evaluation

LANGUAGE English

ABSTRACT An extensive literature review has been conducted as part of an effort to quantify the fidelity of Sandia's lightning burn-through simulation technique. The dominant parameters affecting damage have been identified and are discussed. Two alternative techniques for qualitatively improving the Sandia simulation have been identified, but quantification of the correlation of results of each with those of natural lightning awaits completion of further experimental work. A systematic set of laboratory experiments is proposed to assess the sensitivity of each technique to key simulation parameters. An available calibration linkage to natural lightning is the reproduction of damage spots that were created by lightning on a set of copper disks mounted on TV towers, and an attempt to do this is included in the proposed experiments. In order to reduce the uncertainties of this approach, more lightning-spot data are required, along with records of the lash currents that produced them. It is recommended that such data be acquired in conjunction with the Rocket-Triggered Lightning Program being conducted each summer at the Kennedy Space center.

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80. (*)

AUTHORS Flisowski, Z.; Stanczak, B.; Sikora, J.; Mazzetti, C.

TITLE Investigation of Streamer Discharges from Shielded Electrode at Impulse Voltages Causing Explosion

TYPE conference

PAGE 81-84

CONFERENCE Seventh International Symposium on High Voltage Engineering

LOCATION Dresden, Germany

SPONSOR Dresden University of Technology

DATE Aug. 26, 1991

KEYWORD experimental; simulation; upward streamers

LANGUAGE English

ABSTRACT The authors deal with conditions in which ignition of an explosive mixture may be caused by simulated lightning upward streamers appearing at a shielded and nonshielded single electrode due to impulse voltages. The essential considerations are directed not to inception voltages but to the voltages at which the intensity of discharge is sufficient for the appearance of the event of explosive mixture ignition. Results of danger assessment are based on new experimental data as well as on calculations of electric field distribution. Practical conclusions suitable for lightning protection of structures and arrangements endangered by explosion are formulated.

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81. (***)

AUTHORS Fornes, E.; Ortiz, P.

TITLE Radioactive Lightning Rods, Static Eliminators, and Other Radioactive Devices

TYPE report

PAGE 462-466

SPONSOR Nuclear Regulatory Commission-in rept. "Radioactivity in Consumer Products"

NTIS PB-288 743/8

DATE 1978

KEYWORD radioactive lightning rods; risk/benefit

LANGUAGE English

ABSTRACT COMMENT: This contribution briefly considers the cost/benefits of radioactive lightning rods. The following quote is taken from the report:

"Radioactive lightning rods (RLR) manufactured under several patented designs are claimed to improve the effectiveness of the conventional Franklin conductor, extending its zone of protection by artificial ionization of the air above the rod. The practical principle and effectiveness of this principle have been questioned by a few authors, but no definitive proof has been provided, either theoretically or experimentally. However, we can conclusively demonstrate the practical effectiveness of reliable RLR and the soundness of their specified zone of protection based on a statistical study, which owing to the very nature of the lightning phenomenon, is an appropriate method. As a conservative figure, we estimate the number of RLR installed worldwide to be 200,000, mainly in areas of high frequency of occurrence of lightning discharge. The development of a standard or code of practice to regulate the manufacture, installation, maintenance, and disposal of these devices would be of great benefit to the public, the manufacturing firms, and the appropriate governmental authorities. Such a standard could be developed either by consensus of the technical community involved or by an international regulatory authority."

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82. (**)

AUTHORS Gallimberti, I.
TITLE A Computer Model for Streamer Propagation
TYPE journal
PAGE 2179-2189
JOURNAL Journal of Physics D: Applied Physics
VOLUME 5
DATE 1972
KEYWORD basic; model; streamer
LANGUAGE English
ABSTRACT The propagation of a positive streamer and its basic mechanisms are analyzed in order to find the conditions that an equivalent simplified model must satisfy. Considering the energy balance in the development of secondary avalanches around the streamer tip, an equivalence criterion is derived and used in the formulation of a single-avalanche model. This model reproduces the streamer propagation through a series of successive equivalent avalanches which develop in front of the streamer tip. A number of computer programs have been prepared in order to calculate macroscopic measurable quantities. A first comparison between experimental and computed results shows a satisfactory agreement.

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83. (**)

AUTHORS Gary, C.
TITLE Parameters for H.V. Testing of Various Forms of Air Terminations
TYPE undated preprint
PAGE 1-8
KEYWORD experimental; simulation
LANGUAGE English
ABSTRACT The basis of this study consists of the simulation in the laboratory of the ground field intensity and its variation due to an incoming leader of a real lightning stroke.

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84. (**)

AUTHORS Gary, C.; Hurdubetiu, S.; Dragan, G.
TITLE Downward Negative Lightning and High Voltage Overhead Line Surface Gradients
TYPE conference
PAGE 49-53
CONFERENCE 21st International Conference on Lightning Protection
LOCATION Berlin, Germany
DATE Sept. 21, 1992
KEYWORD basic; experimental; model
LANGUAGE English
ABSTRACT The present paper continues the previous study on negative downward lightning in the vicinity of a high voltage overhead line with ground conductors, with the aim to identify the most stressed line element while the downward negative lightning is approaching the line. The downward lightning and the line structure are modeled using the charge

simulation method, with ring and straight segment equivalent charges. With the discharge channel in the vertical plane containing the tower, the computed surface gradients for different line geometries and downward channel locations allow for the identifying of the upper leader stemming point and the corresponding striking distances.

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85. (***)

AUTHORS Gary, C.; Hutzler, B.
TITLE Simulation of Lightning Attachment to Earthed Structures
TYPE journal
PAGE 18-24
JOURNAL Revue Generale de l'Electricite
NUMBER 3
DATE March 1989
KEYWORD basic; experimental; simulation
LANGUAGE French
ABSTRACT The attachment of lightning to a structure at ground potential is determined by the connection of the stepped leader and an upward discharge occurring from this structure. The authors describe a laboratory procedure based on the development of upward discharges. They review the variation of the electric field generated at ground level by a stepped leader in the case of an actual lightning stroke, and show how that field can be simulated by a laboratory arrangement.

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86. (***)

AUTHORS Gary, C.; Hutzler, B.; Cristesc, D.; Dragan, G.; Enache, R.; Popa, B.
TITLE Laboratory Aspects Regarding the Upward Positive Discharge Due to Negative Lightning
TYPE journal
PAGE 363-377
JOURNAL Revue Roumaine des Sciences Techniques, Serie Electrotechnique et Energetique
VOLUME 34
NUMBER 3
DATE July-Sept. 1989
KEYWORD basic; experimental; simulation; theoretical
LANGUAGE English
ABSTRACT The authors suggest a new method used to study the protection against lightning of any object or even complex sets in laboratory research for the most likely impact points. The upward positive discharge under the lightning leader's field is realized by simulating this field at soil in a laboratory using a large electrode, 10 m in diameter. A slow rise time impulse is applied to this electrode. Finer measurements under this electrode with rods, wire masts, etc. were carried out for corona, leader current, light emitted, and propagation of the discharge. Of the upward leader characteristics, those obtained include the leader inception field, the slope of field variation and the velocity in relation to electrode geometry, wave slope, applied field variation.

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87. (**)

AUTHORS Gayvoronsky, A. S.; Karasyuk, K. V.
TITLE Numerical Model of Lightning Leader Orientation on a Transmission Line
TYPE conference
PAGE 277-280
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD basic; model; theoretical
LANGUAGE English
ABSTRACT Research carried out at the Siberian Research Institute of Energetics with the object of developing a numerical model of propagation and orientation of lightning leaders is presented. In contrast with other known works in this trend, an attempt of description of propagation and orientation of lightning leader is undertaken with considerations for random deviations of its trajectory and inception of upward discharges from grounded structures. On the basis of a Monte-Carlo numerical algorithm, software for an IBM PC was worked out.

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88. (*)

AUTHORS Gayvoronsky, A. S.; Ovsyannikov, A. G.; Razhansky, J. M.
TITLE A Prevention of the Long Spark Leader Channel Turning by Laser Radiation
TYPE conference
PAGE 317-320
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; guided; laser; trajectory
LANGUAGE English
ABSTRACT Obtaining long guided electric sparks can be necessary in solving some practical problems associated with the transportation of charged particles with the construction of plasma antennae. The most promising means to control the trajectory of long sparks is the effect of laser beam radiation. In the known experimental investigations the radiation induced a conducting plasma channel and then the electric field was applied to maintain the plasma created. Here we analyze possibilities for generating long guided sparks where plasma is created and maintained due to the electric field. Under natural conditions the trajectory of such discharges differs essentially from the straight line. On the basis of the results of studying the reasons for turns in discharge trajectories some measures are suggested to eliminate such turns by the effect of laser beam radiation without changes of physical processes in the discharge. In this case lasers of less power than in the above experimental studies are needed.

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89. (***)

AUTHORS	Gillespie, P. J.
TITLE	Ionizing Radiation: a Potential Lightning Hazard?
TYPE	journal
PAGE	577-578
JOURNAL	Nature
VOLUME	208
DATE	Nov. 6, 1965
KEYWORD	lightning strike; ionizing radiation; review; critique
LANGUAGE	English
ABSTRACT	COMMENT: The author points out that there is no evidence that radiotherapy centers, etc. that emit radiation at levels comparable to that used in some lightning protection rods experience lightning strikes any more frequently than other facilities. He raises the questions, "must one therefore conclude that: (a) small sources of ionizing radiation are not effective as lightning attractors? or (b) radiotherapy centers, etc., rarely operate during thunderstorms, and have, so far, been very fortunate."

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90. (*)

AUTHORS	Gockenbach, E.
TITLE	Lightning Discharge Simulation in the Laboratory
TYPE	journal
PAGE	239-247
JOURNAL	Bulletin des Schweizerischen Elektrotechnischen Vereins & des Verbandes Schweizerischer Elektrizitaetswerke
VOLUME	80
NUMBER	5
DATE	March 4, 1989
KEYWORD	experimental; model; simulation
LANGUAGE	English
ABSTRACT	The simulation of a lightning discharge in the laboratory, e.g. for EMC tests on aircraft, requires an exact knowledge of the discharge physical process. Discharge models can be developed with the aid of measurements. The determination of the impact points is by means of a voltage impulse; the determination of the direct and indirect current effects with the aid of a current impulse. Suitable laboratory test systems for both tests are presented.

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91. (***)

AUTHORS	Golde, R. H.
TITLE	Lightning Conductor
TYPE	Book
VOLUME	2
BOOK	Lightning, Volume 2: Lightning Protection
PUBLISHER	Academic Press, New York
DATE	1977

KEYWORD lightning protection; protective zones; striking distance; review; models
LANGUAGE English
ABSTRACT A general survey is given about lightning rods or conductors that have been used and tested up to 1972. The observational, geometrical, and modeling approaches used to estimate the protective zone are briefly discussed. The similarities between lightning and electrical impulse breakdown in large rod-rod and rod-plane air gaps are examined. The concept of striking distance and its use in defining protection zones is introduced. The use and effectiveness of radioactive sources on lightning conductors is considered. It is argued that radioactivity does not significantly increase the effectiveness of a lightning conductor.

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92. (***)
AUTHORS Golde, R. H.
TITLE Occurrence of Upward Streamers in Lightning Discharges
TYPE journal
PAGE 395-396
JOURNAL Nature
VOLUME 160
DATE Sept. 20, 1947
KEYWORD streamers; leader stroke; lightning; theory; observations
LANGUAGE English
ABSTRACT COMMENT: The author discusses the observational evidence for formation of an upward propagating streamer discharge in the final stage of a lightning strike to ground. It is argued that the length of upward streamers increases with the intensity of the lightning discharge, and that for the median value of lightning strokes, upward streamers of about 16 meters may be expected for a stroke to a lightning conductor, or of 5 meters for a stroke to open ground. The report of cases for flat ground strikes where no upward streamer could be observed and where streamers propagated up to 50 meters above ground suggests significant statistical variability in streamer length.

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93. (***)
AUTHORS Golde, R. H.
TITLE The Attractive Effect of a Lightning Conductor
TYPE journal
PAGE 212-213
JOURNAL Journal of Institution of Electrical Engineers
VOLUME 9
DATE May 1963
KEYWORD lightning conductor; model; air breakdown; leader stroke; lightning simulations
LANGUAGE English
ABSTRACT COMMENT: In this letter to the editor the author discusses calculations and extrapolations of laboratory measurements in an endeavour to determine the attractive effect of a lightning conductor and to derive the frequency of direct lightning strokes to overhead transmission lines. Calculations were made of the electrostatic field strength underneath a downcoming leader stroke from which the tip of the leader above ground

was deduced at which an upward streamer would develop from open ground and from a vertical earthed object such as a lightning conductor or transmission tower. It is noted that laboratory test arrangements differ from one another, so that a proportional extrapolation of results from the laboratory to greater distances may not be fully justified. It is suggested that, although more experimental information is clearly required on the breakdown characteristics of laboratory gap arrangements, it appears reasonable to conclude that the average breakdown gradient of a rod-plane gap simulating a lightning stroke to open ground is much greater than that of a rod-rod gap simulating a stroke to a lightning conductor or transmission tower when tested with a voltage that increases at a rate reasonably close to that likely to occur with natural lightning conditions. It is also argued that ideally, laboratory tests on long electric sparks simulating the last stage of a lightning leader stroke should be made with a wavefront of gradually rising steepness with a final rate of the order of a few kilovolts per microsecond.

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94. (***)

AUTHORS	Golde, R. H.
TITLE	Protection of Structures Against Lightning
TYPE	journal
PAGE	1523-1529
JOURNAL	Proceedings of the Institution of Electrical Engineers - Control & Science
VOLUME	115
NUMBER	10
DATE	October 1968
KEYWORD	review; lightning protection; statistical considerations
LANGUAGE	English

ABSTRACT

In contrast to earlier revisions of the original Code of Practice CP1 1943, the latest revision, published in 1965, introduces several important additions and modifications, based on new concepts of lightning protection and taking account of modern building methods and materials. The paper discusses these modifications and the reasons for their introduction.

COMMENT: Relevant to issues concerning effectiveness of ESE devices, the paper contains the following statement: "Claims have been made periodically that the attractive range of a vertical lightning conductor can be greatly increased by fitting a radioactive source to its tip. Any such claims have been refuted convincingly both by tests under natural thunderstorm conditions [1] and by theoretical arguments [2]. The code therefore states in its foreword that such methods are excluded from consideration."

[1] D. Muller-Hillerbrand, 'Beeinflussung der Blitzban durch radioaktive Strahlen und durch Raumladungen', Electrotech. Z., Vol. 83, pp.152-157 (1962).

[2] A. M. Cassie, 'The effect of radioactive sources on the path of a lightning stroke', ERA report 5262 (1968).

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95. (***)

AUTHORS Golde, R. H.
TITLE The Lightning Conductor
TYPE journal
PAGE 451-477
JOURNAL Journal of the Franklin Institute
VOLUME 283
NUMBER 6
DATE June 1967
KEYWORD review; lightning conductor; attractive range; protection zone
LANGUAGE English
ABSTRACT COMMENT: This is the first in a series of papers in a special issue of the journal devoted to the subject of lightning. The paper reviews the history, current practices, and theory of lightning protection based on the lightning conductor. Several issues relevant to ESE systems are touched on in the paper. One concerns the meaning of the zone of protection. The author makes the following statement in the conclusions: "The space protected by a lightning conductor is still subject to further investigation although there are strong reasons to believe that the distance over which a lightning conductor is capable of attracting a lightning discharge is a statistical quantity related to the intensity of the lightning stroke."

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96. (***)

AUTHORS Golde, R. H.
TITLE Lightning and Tall Structures
TYPE journal
PAGE 347-351
JOURNAL IEE Proceedings
VOLUME 125
NUMBER 4
DATE April 1978
KEYWORD observation;lightning; tall structures; point discharges; space charge; striking distance
LANGUAGE English
ABSTRACT The mechanism by which lightning is attracted to an earthed structure of low height is well established, and the distances over which strokes of different intensities are attracted (the so-called striking distances) have been determined. It appears that the numerical values so established do not apply to structures exceeding, say, 20 m in height. In the electric field under a thundercloud, tall structures produce point-discharge currents. Field observations have shown that the resulting space charges can assume the same shape as the visible plume of smoke from a chimney. When a normal negative leader approaches such a positively charged "plume", it will be attracted to it, and unusually long "striking distances" can result. A plume of positive space charge may be broken up by the action of the violent updrafts and downdrafts under an active thundercloud. The resulting pockets of space charge in the atmosphere are held responsible for the branching of earth flashes. They may also be responsible for strikes to points well below the tips of tall structures standing on open ground. On the other hand, it is suggested that structures surrounded by other tall structures or trees are subject to roughly the same striking distances as low structures. It is furthermore suggested that present knowledge is inadequate to determine striking distances for the less frequent positive discharges.

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97. (**)

AUTHORS Goodlet, M. A.
TITLE Lightning
TYPE journal
PAGE 1-21
JOURNAL Journal of the Institution of Electrical Engineers
VOLUME 81
NUMBER 487
DATE July 1937
KEYWORD review; lightning
LANGUAGE English
ABSTRACT The first part of this paper deals with lightning as a physical phenomenon. The formation of thunder clouds is associated with convectional instability of the atmosphere, the separation of charge being effected by resulting upward currents of air. Lightning strokes usually discharge negative electricity into the ground and consist of a preliminary "leader" stroke from cloud to ground followed by a powerful "return" stroke from ground to cloud. A complete flash usually consists of a sequence of such double strokes separated by time-intervals of the order of 10^{-2} sec. The distribution of flashes to earth under a storm center is influenced by the distribution of space charge above the ground and by discontinuities of conductivity in the ground itself.

The second part of the paper deals with the effects of lightning strokes to overhead transmission lines. It is concluded that direct strokes to line conductors are certain to cause flashover: interruption to supply may be minimized either by devices to clear such faults (Petersen coils, expulsion protective gaps), or by overhead earth wires, which will prevent any strokes falling on the line conductors. Strokes to towers and earth wires are unlikely to cause flashover of a line insulated with 9 standard cap-and-pin units, if tower footing resistances are below 10 ohms; footing resistances low enough to prevent flashover with only 3 cap-and-pin units may be impossible to obtain.

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98. (**)

AUTHORS Gosho, Y.
TITLE Enhancement of DC Positive Streamer Corona in a Point-Plane Gap in Air Due to Addition of a Small Amount of an Electronegative Gas
TYPE journal
PAGE 2035-2046
JOURNAL Journal of Physics D: Applied Physics
VOLUME 14
DATE 1981
KEYWORD experiment; corona; air contamination; water vapor; streamer
LANGUAGE English
ABSTRACT When the potential across a positive-point-plane gap in air is increased, discharges proceed in order as follows: intermittent streamer corona, glow corona and spark. The streamer is markedly enhanced by adding a small amount of electronegative gas e.g., Cl_2, NO_2, NO, etc. This is because the streamer can be initiated at a higher potential than its corona onset potential due to extinction of the glow corona. This effect becomes more

marked with increased concentration of the additive. For a gap system mounted in an enclosed chamber (air), the streamer formation is enhanced by successive discharges and a pronounced fall of the sparking potential is expected to occur. This is due to NO_x formation resulting from successive discharges.

COMMENT: It should be noted that water vapor is among the electronegative additives to air considered in this investigation. The discharges were generated at a positive point electrode with a hemispherical tip of stainless steel. For some tests, the gap was irradiated with beta rays from a ^{90}Sr, 100 micro Ci source. Two counteracting effects were observed to occur with increasing water vapor content: 1) an enhancement of the streamer related to an increase in the corona extinction voltage and 2) streamer suppression. The dominant effect of water vapor was found to depend on gap conditions.

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99. (**)

AUTHORS Graf, D.
TITLE Calculation of Corona Discharges in Point to Plane Gaps
TYPE conference
PAGE 53.04
CONFERENCE Third International Symposium on High Voltage Engineering
LOCATION Milan, Italy
DATE Aug. 23, 1979
KEYWORD theory; corona; space charge; electron avalanche
LANGUAGE English
ABSTRACT An application of the charge simulation method for the calculation of spatial and temporal change of space charges in point to plane gaps is described. With a step by step procedure the motion and value change of space charges is calculated by a computer program. The charges are composed of electrons, positive and negative ions and they are simulated by axial symmetrically arranged point or ring charges. The procedure makes it possible to simulate single avalanches and under consideration of the secondary processes also corona impulses at a negative electrode. The development of the field strength, the distribution of space charges and the conduction current are calculated. The frequency of the impulses above the onset voltage can also be given.

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100. (*)

AUTHORS Greig, J. R.; Fernsler, R. F.; Murphy, D. P.; Pechacek, R. E.; Perin, J.; Raleigh, M.
TITLE Laser-Guided Electric Discharges in the Atmosphere
TYPE conference
PAGE 464-467
CONFERENCE Seventh International Conference on Gas Discharges and their Applications
LOCATION London, UK
DATE Aug. 31, 1982
KEYWORD experimental; guided; laser
LANGUAGE English
ABSTRACT Provides an overview of the results obtained in the experiments at the Naval Research Laboratory with particular emphasis on their implication with respect to lightning and

their application to other areas of physics. Reviews the procedures for achieving primary laser-guided, electric discharges. The different results obtained with the primary discharges are described. Discusses the production of secondary discharges and the limited observations made on them.

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101. (*)

AUTHORS Greig, J. R.; Murphy, D. P.; Pechacek, R. E.; Raleigh, M.; Laikin, E.; Hauver, S.
TITLE Pulsed Power Considerations for Laser Guided Discharges and Their Applications
TYPE conference
PAGE 586-589
CONFERENCE 5th IEEE Pulsed Power Conference
LOCATION Arlington, VA USA
DATE June 10, 1985
KEYWORD guided; laser; practical; pulse power; plasma channel
LANGUAGE English
ABSTRACT Laser-guided, electric discharges in the atmosphere have been used to create approximately 1 m-long, air plasma channels. Channel cooling and the interaction of intense relativistic electron beams (REB) with channels in the atmosphere have been studied. These discharges require driving potentials >100 kV to follow the laser-designated path, but only modest stored energy: typically <1000 J and approximately 250 kV were used. Some applications used two-stage discharges wherein a second, lower-voltage capacitor bank was discharged into the air plasma channel. The secondary discharges were tailored for each application which included: channel resistance measurements; the generation of an RF plasma antenna; simulation of nuclear explosion induced lightning; and studies of relativistic electron beam propagation in current carrying channels. The authors describe the different systems used to effect these discharges and consider the design of a system necessary to extend the discharge length to approximately 10 m.

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102. (*)

AUTHORS Greig, J. R.; Pechacek, R.; Raleigh, M.; Vitkovitsky, I. M.; Halle, J.; Fernsler, R.
TITLE Interaction of Laser-Induced Ionization with Electric Fields
TYPE conference
PAGE Pap.80-1380
CONFERENCE AIAA Fluid & Plasma Dynamics Conference
LOCATION Snowmass, CO USA
DATE July 14, 1980
KEYWORD basic; experimental; guided; laser; plasma channel
LANGUAGE English
ABSTRACT The study of long ionized gas channels is of interest for problems ranging from the understanding of lightning to the transport of charged-particle beams in inertial-confinement fusion reactors. The only practical method of creating controlled long ionization channels is the breakdown of a gas by intense laser beams. Studies to determine the response of such laser spark chains to applied electric fields have been performed, and have shown that laser induced breakdown provides a well controlled

means of guiding electrical discharges. New studies have now determined the electrical and dynamic properties of laser-guided discharge channels. By coupling these measured electrical and dynamic properties to simple analytical models, a clearer picture of the generation and evolution of hot air channels has emerged.

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103. (**)

AUTHORS Griffiths, R. F.; Phelps, C. T.
TITLE A Model for Lightning Initiation Arising from Positive Corona Streamer Development
TYPE journal
PAGE 3671-3676
JOURNAL Journal of Geophysical Research
VOLUME 81
NUMBER 21
DATE July 20, 1976
KEYWORD model; streamer; corona; lightning initiation
LANGUAGE English
ABSTRACT A numerical model is used to calculate the electric field enhancement in a thundercloud due to the propagation of a growing system of positive corona streamers, such as might be initiated by a hydrometeor. These streamers intensify if the ambient electric field E exceeds a critical value E_o, which is experimentally determined. The positive charge carried in the head of the system increases in magnitude, and the negative charge is deposited in the tail, and thus an electric dipole that tends to enhance the original field is created. The growth is calculated by solving an energy balance equation for the system, including the potential energy of the dipole, the losses due to ionization and excitation, and the production of new streamer tips. Several systems may propagate sequentially, each one passing into the debris of its predecessors and growing more vigorously as a result. For representative values of E and E_o at 6.5-km altitude it is shown that a series of three to seven such systems can give rise to local enhancement of the ambient electric field up to 15×10^5 V/m over a distance of a few meters, which is sufficient to insure dielectric breakdown and possibly launch the stepped leader.

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104. (**)

AUTHORS Grzybowski, S.; Jenkins, E. B.
TITLE Estimation of Lightning Performance on Models of 115kV Transmission Lines
TYPE conference
PAGE 325-328
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; guided; ionizing terminal; model; spline ball ionizer
LANGUAGE English
ABSTRACT This paper presents the experimental results of a study on the effectiveness of the spline ball ionizers (dissipators) for lightning protection of transmission lines. The evaluation was based on the measurements of CFO voltage between transmission lines and cloud

models. The discussion of results follows the presented data. Comparison of probability to hit the transmission line by lightning stroke for different shielding types of transmission lines is given.

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105. (**)

AUTHORS Guenfoud, O.; Jordan, I. B.; Saint-Arnaud, R.
TITLE Atmospheric Ions and Positive Point Corona
TYPE conference
CONFERENCE Fourth International Symposium on High Voltage Engineering
LOCATION Athens, Greece
DATE Sept. 5, 1983
KEYWORD experiment; corona; time lag; negative-ion density
LANGUAGE English
ABSTRACT The relation between the time lag of corona formation in air under surge voltage and the concentration of negative ions and air humidity has been studied. Atmospheric ion concentration was modified by using a point ionizer or a radioactive source of 14^C. Ion density was measured by a Gerdien ion counter. It was found that electron detachment provides an essential source of initiatory electrons. The influence of this source can be modified by high air humidity.

COMMENT: The results of this laboratory study point to the role played by negative ions in the initiation of a streamer from a lightning rod via electron detachment processes in the air surrounding a rod, and the significant influence that water vapor can have on the detachment rate and thus the discharge initiation probability.

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106. (**)

AUTHORS Gumley, J. R.
TITLE Lightning Interception
TYPE conference
PAGE 136-141
CONFERENCE Electric Energy Conference 1989: Electrical Services for Buildings. Preprints of Papers
LOCATION Sydney, NSW, Australia
SPONSOR Natl. Comm. Electr. Energy Coll. Electr. Eng.
DATE Oct. 24, 1989
KEYWORD lightning protection; review
LANGUAGE English
ABSTRACT The historical development of lightning interception concepts is discussed. Existing and past methods of developing safe zones below protection systems are compared. The more rigorous collection volume design concept is applied to three dimensional structures. The design allows engineers to plan protection systems based on 'risk of bypass' conditions. The efficiency of any protection design method is shown to be limited by lack of information on the relative performance of various forms of air terminals under storm conditions. Tests are described which show the upward leader development currents from equally exposed air terminals. Initial results indicate the long promoted sharp (Franklin) rod may have inferior performance when compared with other geometric shapes.

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107. (**)

AUTHORS Gumley, J. R.
TITLE Lightning Interception and the Upleader
TYPE conference
CONFERENCE 22nd International Conference on Lightning Proctection
LOCATION Budapest, Hungary
DATE Sept. 19, 1994
KEYWORD observations; lightning; current; air terminal; leader; streamer
LANGUAGE English
ABSTRACT An interim report is provided showing measurements of air terminal emission currents under natural storm conditions. The report covers two events recorded at Darwin, Australia, in which emission currents exceeded 20 Amperes. Current levels and characteristics from some terminals are consistent with those of non-intercepting up leaders. Others produced streamer type emissions without the continuing currents associated with leader progression. The comparative performance of different geometric shapes is discussed together with the up leader progression characteristics. Finally, comparison is made with long gap laboratory discharges.

COMMENT: In the conclusion of this paper it is remarked that the results indicate significant performance differences between air terminals of various physical and electrical geometries when at equal height and exposed to the same natural conditions.

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108. (***)

AUTHORS Gumley, J. R.; Invernizzi, C. G.; Khaled, M.; Wallhausen, C. W.
TITLE Coaxial Lightning Protection for Land and Marine Telecommunications
TYPE journal
PAGE 52-55
JOURNAL Communications International
VOLUME 4
NUMBER 9
DATE Sept. 1977
KEYWORD coaxial line protection; ionizing source
LANGUAGE English
ABSTRACT The article discusses the role of ionizing sources in ensuring the rapid generation of an avalanche leading to the formation of the lightning streamer. It shows how a practical electrode assembly is coupled to a patented coaxial down conductor to form a unique integrated lightning protection system. The article also describes an integrated lightning protection system which employs an electrode assembly by electron sources. The electrode is coupled to a high voltage coaxial down conductor which contains the discharge in its passage to ground.

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109. (***)

AUTHORS Gumley, J. R.; Invernizzi, C. G.; Khaled, M.; Wallhausen, C. W.
TITLE Nuclear Lightning Protection and the New Coaxial Lightning Protection System
TYPE report
PAGE 448-461
SPONSOR Nuclear Regulatory Commission-in rept. "Radioactivity in Consumer Products"
NTIS PB-288 743/8
DATE 1978
KEYWORD radioactive air terminals; lightning; protection failures; striking distance
LANGUAGE English
ABSTRACT COMMENT: In this contribution, the author's review various aspects of lightning protection and present some interesting statistical data and examples of failures of convention lightning rods. They describe radioactive air terminals and express favorable opinions about the effectiveness and operation of these devices. Concerning the issues of integrity and safety of the radioactive sources used in lightning rods, the authors make the following statements in their report:

"The Am-241 sources used in the 'E.F.' [electricite froide] system are produced by the same basic production processes used in the manufacture of sources used in smoke detectors, but they are subject to more stringent quality and integrity controls and they incorporate additional noble metal seals. Because of physical form and insolubility of Am-241 in body fluids, ingestion does not raise a problem and an inhalation hazard is extremely unlikely."

"Since radioactivity can be a hazard to health and safety, it is necessary to determine the relative hazard of the use of Americium in 'E.F.' systems and whether the benefits of such usage outweigh any risks involved. Radiation levels from installed units at points where personnel exposure might occur are too low to be detected with ordinary detection devices. In the remote chance of an accident involving an 'E.F.' system, there is little or no chance of scattering radioactive material."

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110. (***)

AUTHORS Gumley, J. R.; Invernizzi, C. G.; Khaled, M.
TITLE Lightning Protection: A Proven System
TYPE journal
PAGE 114-120
JOURNAL Fire Technology
VOLUME 13
NUMBER 2
DATE May 1977
KEYWORD coaxial grounding conductor; ionization terminal
LANGUAGE English
ABSTRACT A unique integrated lightning protection system is described, which uses an electrode assembly enhanced by electron sources. The electrode is coupled to a high voltage coaxial grounding conductor to offer hitherto unattainable performance. Design features of the discharge mechanism, the ionizing terminal, and the coaxial conductor are outlined.

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111. (**)

AUTHORS Hagenguth, J. H.
TITLE Photographic Study of Lightning
TYPE journal
PAGE 577-585
JOURNAL Transactions of the American Institute of Electrical Engineers
VOLUME 66
DATE 1947
KEYWORD observations; lightning; photography; time development; leaders
LANGUAGE English
ABSTRACT COMMENT: This paper reports the results from time-resolved photographic observations of lightning discharges at a lightning observatory on top of the office buildings of the General Electric Company in Pittsfield, Massachusetts. Statistical information was recorded about the multiplicity of strokes, number of current peaks, stroke density, storm-day expectancy, leader velocity, and vertical height of cloud-to-ground strokes. The following conclusions were offered:

1. The photographic method gives a very good tool to obtain a considerable number of valuable statistical information on the characteristics of lightning strokes at minimum expense.

2. It has been confirmed that a large number of strokes have long durations and that continuing currents are of frequent occurrence, both factors being important in the operation of transmission and distribution circuits.

3. The investigation has shown that lightning phenomena in Pittsfield are of essentially the same character as in other parts of the world.

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112. (**)

AUTHORS Hagenguth, J. H.; Anderson, J. G.
TITLE Lightning to the Empire State Building Part III
TYPE journal
JOURNAL Transactions of the American Institute of Electrical Engineers
VOLUME 71
DATE August 1952
KEYWORD observations; lightning; Empire State Building; current measurements
LANGUAGE English
ABSTRACT Previous papers have reported lightning investigations conducted at the Empire State Building in New York City during the years 1935 through 1940. During 1941, 1947, 1948, and 1949 further data were obtained on all lightning stroke characteristics. This paper presents a summary of all data obtained during the 10 years in the form of frequency curves.

1. The majority of the strokes at the Empire State Building start with an upward stepped leader followed by a continuous discharge with an average amplitude of 250 amperes. For about 50 per cent of the strokes this discharge mechanism is followed by one or more

current peaks (average 2.3) of much higher amplitude. The current peaks are initiated by downward continuous leaders.

2. Proof has been obtained of the existence of continuous current by oscillographic and photographic methods.

3. Fifty per cent of the strokes have a total charge in excess of 19 coulombs. The maximum measured was 164 coulombs.

4. The maximum stroke duration was 1.5 seconds while 50 per cent of the strokes were in excess of 0.27 second.

5. The wave shapes, front and tail, and current crests for 80 current peaks were determined.

6. Rates of rise of current peaks frequently are 10 to 20 kiloamperes per microsecond but may be as high as 50 kiloamperes per microsecond.

7. Good agreement is shown with data by other investigators.

8. The application of the data to transmission line problems is discussed.

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113. (***)

AUTHORS Hartmann, G.; Gallimberti, I.

TITLE The Influence of Metastable Molecules on the Streamer Progression

TYPE journal

PAGE 670-680

JOURNAL Journal of Physics D: Applied Physics

VOLUME 8

DATE 1975

KEYWORD model; basic; metastables; plasma channel

LANGUAGE English

ABSTRACT The measurement of the de-activation rate of the N_2 vibrational metastables produced by a gas discharge in short gaps at atmospheric pressure indicates that their concentration remains significantly high for some hundreds of microseconds. As a consequence, when the discharge frequency is larger than a few thousand Hertz, the discharge development may be influenced by the presence of metastable molecules left in the gap by previous discharges. The evolution in time of the metastables in air at atmospheric pressure has been analyzed according to the creation and destruction processes. The theoretical interpretation is consistent with the experimental results on the decay of the N_2 vibrational metastables. The effect of a pre-existing metastable trail on the streamer propagation has been analyzed according to an energetic criterion. It is suggested that the metastable molecules act as a reserve of energy which is transferred to the electrons in superelastic collisions. The balance of the energy exchanges is analyzed in detail: this makes possible an explanation of some peculiarities in the behaviour of repetitive discharges. The energetic criterion predicts the possibility of a stable streamer propagation, even without an applied field, when the concentration of metastable molecules is sufficiently high: this prediction has been experimentally confirmed.

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114. (**)

AUTHORS Heary, K. P.; Chaberski, A. Z.; Gumley, S.; Gumley, J. R.; Richens, F.; Moran, J. H.

TITLE An Experimental Study of Air Terminal Performance as a Function of Geometrical Shapes

TYPE conference

PAGE 1-7

CONFERENCE French-Japanese Workshop

LOCATION Deauville, France

DATE July 15, 1989

KEYWORD experimental; Franklin rod; guided; humidity; ionizing terminal; outdoor test

LANGUAGE English

ABSTRACT Measurements were taken of ion currents for different types of air terminals in an outdoor area. The ion current of air terminals is related to the attractiveness of the terminal to a lightning strike. The lightning strike attractive power of air terminals depends on sustained, not quenched Townsend avalanche at the tip of the air terminal, which produces a streamer under thunderstorm conditions. The formation of a strong sustained streamer depends on ion concentration at the tip of the air terminal, therefore, it is important to determine the limits of ion concentration for optimal performance of the air terminal. In general, ion current of air terminals produced by applying bias in the 5 kV to 40 kV range is slowly increasing and corresponds to the increasing attractive power of flashover of air terminals under thunderstorm conditions. The ion current in the range from 40 kV to 70 kV is rapidly increasing and going into corona discharge, and it corresponds to the decrease of attractive power of flashover. Therefore, a strong corona current is not contributing to the improvement of the lightning strike attractive power of air terminals.

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115. (**)

AUTHORS Heary, K. P.; Chaberski, A. Z.; Gumley, S.; Gumley, J. R.; Richens, F.; Moran, J. H.

TITLE An Experimental Study of Ionizing Air Terminal Performance

TYPE conference

CONFERENCE IEEE Power Engineering Society

LOCATION Portland, Oregon

DATE July 24, 1988

KEYWORD experimental; Franklin rod; guided; humidity; ionizing terminal; outdoor test; simulation

LANGUAGE English

ABSTRACT An experimental study of the performance of ionizing air terminals versus non-ionizing air terminals is reported. Radioactive sources were used to obtain ionization of the air surrounding the tip of the air terminals. The tests were conducted at the John Lapp High Voltage Laboratory under conditions approximating the natural setting. The tests were performed in an outdoor area of the laboratory. Tests were made during both rain/fog and clear weather with the natural bias produced by the clouds above the testing area, and also under artificial bias. This arrangement permitted the study of the high relative humidity effects conducive to the successful functioning of the ionizing air terminals.

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116. (***)

AUTHORS Heary, K. P.; Chaberski, A. Z.; Gumley, S.; Gumley, J. R.; Richens, F.; Moran, J. H.
TITLE An Experimental Study of Ionizing Air Terminal Performance
TYPE journal
PAGE 1175-1184
JOURNAL IEEE Transactions on Power Delivery
VOLUME 4
NUMBER 2
DATE April 1989
KEYWORD ionizing terminal; tests; lightning simulations; Franklin rod; experiment; humidity effect
LANGUAGE English
ABSTRACT

An experimental study of the performance of ionizing air terminals versus non-ionizing air terminals is reported. Radioactive sources were used to obtain ionization of air surrounding the tip of the air terminals. The tests were conducted at the John Lapp High Voltage Laboratory at LeRoy, New York under conditions approximating the natural setting. The tests were performed in an outdoor area of the laboratory. Tests were made during both rain/fog and clear weather with the natural bias produced by the clouds above the testing area, and also under artificial bias. This arrangement permitted the study of the high relative humidity effects conducive to the successful functioning of the ionizing air terminals. Some tests were conducted at low humidity in sunny weather for the sake of comparison. All the tests were performed on a comparison basis in which a radioactive air terminal was compared directly with a non-radioactive air terminal. Both air terminals had exactly the same geometrical configuration in each test conducted. The standard (non-radioactive) air terminal chosen was the Franklin Rod. The tests results indicate a substantial superiority for the ionizing terminal when tested under realistic conditions. These results are in agreement with those obtained in field installations.

COMMENT: This work deserves careful consideration because the results and conclusions would appear, at least on the surface, to be contrary to other published work which suggest that use of radioactive ionizing sources does not significantly improve the performance of a lightning rod. The controversial nature of this work is reflected in the discussions published with the paper by: 1) Giangido Carrara (CESI, Milano, Italy); 2) Ian S. Grant (Power Technologies, Inc., Schenectady, New York); 3) A. C. Liew (Department of Electrical Engineering, National University of Singapore, Singapore 0511); 4) C. Menemenlis (University of Patras-Greece); and 5) Abdul M. Mouse (British Columbia Hydro, Vancouver, BC, Canada). All of the contributors to the discussion raise serious doubts or questions about the validity or significance of the conclusions presented in this work as apply to air terminal performance. It would appear, for this work as for all other laboratory or small-scale simulations of lightning, that the issues concerning appropriateness of the test configuration and validity of extrapolations to much larger scales that apply to natural lightning are problematic. Nevertheless, the results appear to be valid and add to our understanding of the electrical breakdown process in air.

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117. (**)

AUTHORS Heary, K. P.; Chaberski, A. Z.; Richens, F.; Moran, J. H.
TITLE An Experimental Study of Corona-Ion Current of Air Terminals
TYPE conference

PAGE	349-354
CONFERENCE	2nd International Conference on Applied Electrostatics
LOCATION	Beijing, China
DATE	Nov. 4, 1993
KEYWORD	corona; experimental; Franklin rod; geometry; outdoors; simulation
LANGUAGE	English
ABSTRACT	An experimental study of the geometry influence on the performance of air terminals is reported; the geometrical modification of the physical conditions in close proximity to the tip of a simple Franklin Rod was used. This electric stress modification was obtained by introducing a metallic, hollow ellipsoid through which a Franklin Rod passes with its sharp tip protruding above the top surface of the spheroid. All tests were conducted in an outdoor area. The tests were performed under different atmospheric conditions, which included high and low relative and absolute humidity and the application of natural and artificial bias. The proper conditions for testing air terminals are those which exist during the thunderstorms: high humidity and electric bias, but tests also included fair weather conditions. All tests were performed on a comparison basis using the Franklin Rod air terminal as a standard reference. The experimental test arrangement used reflected closely that of nature, namely an extended flat rectangular terminal parallel and above the ground which served as a "cloud terminal."

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118. (**)

AUTHORS	Heary, K. P.; Chaberski, A. Z.; Richens, F.; Moran, J. H.
TITLE	Early Streamer Emission Enhanced Air Terminal Performance and Zone of Protection
TYPE	conference
PAGE	26-32
CONFERENCE	Proceedings of the IEEE/IAS Industrial and Commercial Power Systems Annual Technical Conference
LOCATION	St. Petersburg, FL USA
SPONSOR	IEEE
DATE	May 2, 1993
KEYWORD	experimental; Franklin rod; geometry; ionizing terminal
LANGUAGE	English
ABSTRACT	An experimental study of the performance of ionizing air terminals versus non-ionizing air terminals is reported. Radioactive sources were used to obtain ionization of the air surrounding the tip of the air terminals and also ionization due to field amplification, by the geometrical shape was included. The tests were conducted at the John Lapp High Voltage Laboratory under conditions approximating the natural setting. The tests were performed in an outdoor area of the laboratory. All the tests were performed on a comparison basis in which an enhanced air terminal was compared directly with a non-enhanced air terminal of the same geometry or against a standard rod (Franklin air terminal). The test results indicate a substantial superiority for the enhanced air terminal. Zone of protection is also defined and is based on a electrogeometric model including enhanced flexible dynamic length.

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119. (*)

AUTHORS	Heidler, F.
TITLE	Lemp Calculation and Lightning Current Function
TYPE	conference
PAGE	237-240
CONFERENCE	8th International Symposium on High Voltage Engineering Proceedings, vol. 4
LOCATION	Yokohama, Japan
SPONSOR	IEE of Japan
DATE	Aug. 23, 1993
KEYWORD	basic; model
LANGUAGE	English
ABSTRACT	During the so-called return stroke period the lightning current is flowing along the lightning channel to earth. The lightning channel acts as a transmitting antenna radiating the lightning electromagnetic impulse (LEMP). Lightning discharge models were developed to describe the interdependencies between the LEMPs and the initiating currents. They can be used to reconstruct the lightning currents from the experimental LEMP data. For far distances it may be advantageous to recalculate the lightning currents directly from the recorded fields. For near distances normally the lightning current is considered to be an input parameter for the LEMP calculation. The method requires a current function, which can be varied easily and which delivers satisfying coincidences to measurements. Since with existing current functions the field derivatives especially of positive and negative first earth strokes could not be simulated satisfactorily, it becomes necessary to deduce a more suitable current function.

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120. (**)

AUTHORS	Hierl, A.
TITLE	Characteristics of Triggered Lightning
TYPE	conference
PAGE	11-18
CONFERENCE	ICLP'85: 18th International Conference on Lightning Protection
LOCATION	Munich, Germany
DATE	Sept. 16, 1985
KEYWORD	basic; practical; rocket; triggered
LANGUAGE	German
ABSTRACT	Lightning is triggered by trailing a wire from a rocket sent into a thundercloud. The current components of a lightning triggering, which occur in the wire and after its vaporization in the plasma channel from the rocket's start to the end of the discharge, are estimated and discussed. Examples are shown for the quasi-continuous and impulse currents during the rise of the wire. The main discharges are split up into different types depending on the magnitude of the impulse energy compared with the energy needed for the wire's vaporization. The charge lowered during a lightning triggering, together with the change of the electric ground field strength, allows calculation of the height of the neutralized charge center and a statement on the length of the leader.

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121. (*)

AUTHORS Hirohashi, M.; Miyata, H.; Sakae, C.; Sakai, T.; Uchiyama, T.
TITLE Triggering Lightning by Laser Produced Plasma
TYPE conference
PAGE 310-313
CONFERENCE Conference on Lasers and Electro-Optics
LOCATION Baltimore, MD USA
DATE April 24, 1989
KEYWORD applications; laser; pulse power; theoretical; triggered
LANGUAGE English
ABSTRACT Laser triggering and guiding of a long interelectrode flashover, aimed at triggering lightning, have been studied. Some results of producing a plasma channel in air with a pulsed unstable-mode TEA CO_2 laser and an experiment on triggering and guiding the interelectrode flashover by the plasma channel are reported. Numerical calculations of the peak intensity of a focused laser beam and the length of the plasma as a function of beam propagation distance were performed and compared with experiment.

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122. (*)

AUTHORS Hojo, J.; Ishii, M.; Kawamura, T.; Suzuki, F.; Komuro, H.; Shiogama, H.
TITLE Seasonal Variation of Cloud-to-Ground Lightning Flash Characteristics in the Coastal Area of the Sea of Japan
TYPE journal
PAGE 13207-13212
JOURNAL Journal of Geophysical Research
VOLUME 94
NUMBER D11
DATE Sept. 30, 1989
KEYWORD observations; lightning; statistical distributions; seasonal variations
LANGUAGE English
ABSTRACT Cloud-to-ground lightning flashes in a coastal area of the Sea of Japan have been observed for a few years by a magnetic direction-finding system for lightning return strokes. Through the operational evaluation of the system, the data obtained so far have been carefully analyzed and corrected. In winter the activity of lightning does not move inland farther than 20-30 km from the coastline, and most of the flashes are detected on the sea. Seasonal variations are also found in polarities and magnetic signal strengths of lightning return strokes.

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123. (*)

AUTHORS Honda, C.; Nakazawa, M.; Takuma, T.; Uchino, K.; Muraoka, K.; Kinoshita, F.; Katahira, O.; Akazaki, M.
TITLE A Study on Laser-Induced Discharge in Atmospheric Air(II)
TYPE conference
PAGE 289-292
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3

LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD basic; experimental; laser; plasma channel; triggered
LANGUAGE English
ABSTRACT As a basic study on future laser-induced lightning, laboratory-scale experiments of discharge (sparkover) induction have been performed for long gaps in the atmosphere using a CO_2 laser. The 50% sparkover voltage takes a minimum at a delay time of impulse voltage application from 50 to 200 μs after firing the laser. It shows a remarkable polarity effect in the non-uniform field condition such as a plane-to-rod configuration. Laser-produced plasmas behave like conductive particles as demonstrated by a simulation experiment with metal beads.

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124. (**)
AUTHORS Horii K; Sakurano, H.
TITLE Observation of Final Jump of the Discharge in the Experiment of Artificially Triggered Lightning
TYPE journal
PAGE 2910-2917
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS104
NUMBER 10
DATE 1985
KEYWORD experiment; triggered lightning; leader stroke; striking distance
LANGUAGE English
ABSTRACT The final striking discharges to a power line or to the ground were observed from near site in the experiment of triggered lightning with rocket in winter of Japan. The leader stroke propagated downwards apart from the grounded wire trailed by the rocket with branching and bending in every stepping point. The final striking distance was related to the peak discharge current comparing with the curves in the literatures

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125. (***)
AUTHORS Hughes, J.
TITLE Review of Lightning Protection Technology for Tall Structures
TYPE report
SPONSOR Office of Naval Research, Arlington, Virginia
DATE Jan. 1, 1977
NTIS AD-A075
KEYWORD lightning protection; review; corona-point arrays
LANGUAGE English
ABSTRACT COMMENT: The collection of papers and reported discussions in this volume represent an attempt to make some evaluation of the ability of corona-point arrays to absorb, suppress, eliminate, or in some way, protect against direct strike of lightning to surface structures. Those impaneled for the review and discussion are from the best informed

investigators of lightning phenomena in the country. In addition, the volume contains two invited papers from Great Britain. The discussions center mainly around the operation of a commercial product known as a corona-point array which is intended to protect a structure and the area around it from lightning strike by in some way suppressing the stroke as distinguished from the operation of the lightning rod, which protects by conducting the lightning through a predetermined, low resistance path to ground. Although this review has not settled in any final way what, if any, is the effect of corona-point discharge on lightning propagation or direction of movement, or what the optimum technology of protection is, it has, nevertheless, illuminated certain other questions and particularly that of the efficiency of blunt or pointed rods for lightning protection. From the verbatim recordings of the discussions of corona-point arrays and related topics one can find expressions of conviction without reservation that such devices do not work to statements of guarded skepticism about their performance to testimonials on their good performance.

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126. (***)

AUTHORS Hutzler, B.
TITLE Comparison of Lightning and Long Spark
TYPE journal
PAGE 12-17
JOURNAL Revue Generale de l'Electricite
NUMBER 3
DATE March, 1989
KEYWORD experimental; practical; simulation; simulation evaluation
LANGUAGE French
ABSTRACT Lightning and long sparks (several meters in length) present obvious similarities. The author examines whether it is possible to use long sparks to simulate lightning and its effects. In the first part of the article, the phenomena are compared qualitatively. In both cases the negative leader is stepped while the positive leader propagates continuously. The different aspects which can be simulated in the laboratory are deduced: the leader propagation and the associated electromagnetic radiation on the one hand and the attachment mechanism on the other. The second part is a quantitative comparison which shows the differences in propagation velocity and current. The scale factor, which limits the possible applications, is quickly discussed but requires further work.

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127. (**)

AUTHORS Hutzler, B.
TITLE Lightning Simulation
TYPE journal
PAGE 31-40
JOURNAL Electricite de France, Bulletin de la Direction des Etudes et Recherches, Serie B: Reseaux Electr. Materiels Electr.
VOLUME 0
NUMBER 3
DATE 1988

KEYWORD experimental; simulation; simulation evaluation
LANGUAGE French
ABSTRACT A comparative study of lightning and of the long spark is presented. The different features of lightning which can be simulated in a high voltage laboratory are deduced: the electromagnetic radiation of the predischarges and the definition of the attachment point. The relevant testing techniques are described. This article has been presented during the technical and scientific days of the A.S.T.E. (Society for the development of environmental engineering).

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128. (**)
AUTHORS Hutzler, B.; Hutzler-Barre, D.
TITLE Leader Propogation Model for Predetermination of Switching Surge Flashover Voltage of Large Air Gaps
TYPE journal
PAGE 1087-1096
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS-97
NUMBER 4
DATE July/Aug 1978
KEYWORD model; leader propagation; point-plane gaps; switching surge; air breakdown
LANGUAGE English
ABSTRACT The breakdown voltage of an air gap submitted to switching surges may be predetermined by use of a mathematical model of leader propagation. This model is applied, in this article, to point plane gaps, for which a number of experimental results are available. It is possible to simulate the development of a flashover: current, speed, visual appearance. U_{50} voltage and standard deviation may be deduced by simulation of test sequences and, as a result, the variations of these parameters, when the length of the gap and the shape of the applied wave vary, may be studied. Generally, results are found to be in accordance with experiments.

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129. (*)
AUTHORS Imada, G.; Kuroda, T.; Ohmomo, T.; Saiki, K.; Masugata, K.; Yatsui, K.; Yasuoka, T.; Tamagawa, S.; Satoh, S.; Gotoh, T.
TITLE Pulse-Power Technology and its Applications to Artificial Control of Lightning
TYPE conference
PAGE 309-312
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; laser; pulse power; triggered
LANGUAGE English
ABSTRACT R&D on pulse-power technology has been carried out since the establishment of our university in 1978. Charged particle beams of electrons or ions are produced to create

extremely high power density in a very short time. Associated various applications are available. Here, one of their applications is introduced to control lightning artificially. The breakdown characteristics of a short-distance discharge gap in the atmosphere have been studied by TEA-CO_2 laser. We have found the probability of a electrical breakdown being induced is significantly enhanced if the focal point is set behind the discharge gap or near the negative high-voltage electrode. Diffusing 3 μm diameter aluminum particles in atmosphere, the optical breakdown threshold is lowered to 15 MW/cm^2 compared to 0.5 GW/cm^2 in the absence of micro particles.

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130. (***)

AUTHORS Immelman, M. N. S.
TITLE Point-discharge Currents During Thunderstorms
TYPE journal
PAGE 159-163
JOURNAL Philosophical Magazine
VOLUME 25
NUMBER 166
DATE January 1938
KEYWORD observations; corona; thunderstorms
LANGUAGE English
ABSTRACT COMMENT: This is a relatively short paper in which results are presented from measurements of current associated with corona (point discharges) generated during thunderstorms at a point mounted on a 7 m pole. The significant feature of this work relevant to lightning protection is that the corona current was found to vary considerably with atmospheric conditions during a storm such as wind intensity, presence of dust, and overall severity and duration of the storm.

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131. (*)

AUTHORS Iris, M.; Shinkai, T.; Araki, K.; Yoshikawa, S.
TITLE Temporal Decay of an Atmospheric Plasma Leader Stroke for Lightning Initiation
TYPE conference
PAGE 576-579
CONFERENCE Proceedings of the Tenth International Conference on Gas Discharges and their Applications, vol. 2
LOCATION Swansea, UK
DATE Sept. 13, 1992
KEYWORD experimental; guided; laser; triggered
LANGUAGE English
ABSTRACT In relation to the lightning protection problems of over 100 m of high power transmission networks of UHV (1 MV transmission) Project in Tokyo Electric Power Company, a series of extensive researches on lightning initiation/guidance by laser produced plasma is in progress. This process looks like initiating the plasma channel between cloud and ground, just like a leader stroke. The mechanism causing the qualitative transition from leader stroke to lightning discharges should be closely related to the mechanism controlling restriking condition in power circuit breaker arcs.

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132. (*)

AUTHORS Itatani, R.; Kubo, M.; Jinno, M.; Nagano, G.; Sonoi, Y.; Nagai, T.
TITLE Fundamental Research on Laser Triggered Lightning Using a New Technique
TYPE conference
PAGE 301-304
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD crossbeams method; experimental; guided; laser; triggered
LANGUAGE English
ABSTRACT Superposition of two laser beams is demonstrated to be more effective in producing a plasma than one strong laser beam. Also, by producing laser plasmas between an electrical discharge gap, such advantages as to trigger and to guide a discharge, to control the delay time of discharge, and to reduce 50% flashover voltage are made clear. These results encourage us to promote the crossbeams method for laser-triggered lightning.

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133. (*)

AUTHORS Jacobson, E. A.; Krider, E. P.
TITLE Electrostatic Field Changes Produced by Florida Lightning
TYPE journal
PAGE 103-117
JOURNAL Journal of Atmospheric Sciences
VOLUME 33
DATE January 1976
KEYWORD observations; lightning; electric field measurement
LANGUAGE English
ABSTRACT The electrical behavior of thunderstorms triggered by local heating and sea-breeze convergence, a low pressure disturbance, and a weak frontal passage has been studied at the NASA Kennedy Space Center, Florida. A nonlinear least-squares minimization procedure has been developed to describe changes in the total electrostatic field produced by lightning in terms of point charge models for the cloud charge distributions. The results of this analysis indicate that discharges to ground usually neutralize cloud charges in the range from -10 to -40 C. The computed charge altitudes for Florida are somewhat higher than for other geographical locations 6 to 9.5 km, but the corresponding ambient air temperatures, -10 to -34 degrees centigrade, are similar. A large fraction of the discharges to ground show total field changes which are small or even reversed in polarity within 3 km of the discharges. An analysis of these cases suggests that ground discharges often neutralize a small positive charge, 0.5 to 4 C at altitudes of 1 to 3 km, in addition to the larger negative charge higher in the cloud.

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134. (**)

AUTHORS Janischewskyj, W.; Hussein, A. M.; Dziurewicz, P.; Shostak, V.
TITLE Characterization of the Current Wavefront Parameters of Lightning Strikes to the CN Tower in Toronto
TYPE conference
PAGE 221-224

CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD basic; experimental; field observations
LANGUAGE English
ABSTRACT The 553 meter height of the CN Tower in Toronto ensures that it receives many tens of lightning flashes each year. Comprehensive measurements of significant parameters for lightning strikes to the tower have been performed since 1990. The current derivative was recorded at the tower, using a 40 MHZ Rogowski coil, by 10-bit, 10-ns, computer controlled digitizer, with long segmented memory. This paper analyzes in detail wavefront parameters of lightning current for negative upward flashes observed at the tower in 1991. In addition to the absolute peak value, the maximum steepness, and the risetime, other parameters useful in describing the wavefront of the lightning current are considered. Data collected at the CN Tower are compared with those obtained at shorter structures, and those observed in tests with artificially triggered lightning.

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135. (*)
AUTHORS Jones, B.
TITLE Switching Surges and Air Insulation
TYPE journal
PAGE 165-180
JOURNAL Philosophical Transactions Royal Society of London A
VOLUME 275
DATE 1973
KEYWORD air breakdown; switching surges; positive impulse; corona; review; theory
LANGUAGE English
ABSTRACT Some thirteen years ago, a reduction was noticed in the strength of air insulation when subjected to slowly rising positive impulse voltages such as occur during switching operations on power systems. Methods for the prediction and control of switching overvoltages have been established and empirical data collected in high voltage laboratories. Insulation against switching surges is now seen as an important factor in the feasibility of power transmission at ultra-high voltages. The strength of large air gaps depends not only the geometry of the gap (point-plane, rod-rod, etc.), but also on the waveshape of the applied voltage. The practical diversity of gaps and waveshapes is such that a sound theoretical approach must be found if laboratory testing is to be kept within bounds. Qualitative understanding of the breakdown processes in long air-gaps has advanced rapidly in the last two years. Predictive mathematical models are now being constructed.

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136. (**)
AUTHORS Kalinin, M. I.
TITLE Mechanism of Corona-to-Spark Transition in Long Air Gaps
TYPE journal
PAGE 948-951

JOURNAL	Soviet Physics-Technical Physics
VOLUME	10
NUMBER	7
DATE	Jan. 1966
KEYWORD	theory; corona; streamer; leader; space charge
LANGUAGE	English
ABSTRACT	COMMENT: This paper is concerned with the theory of electrical breakdown in long air gaps. The formation of a spark channel in long air gaps with highly nonuniform field is preceded by a corona discharge in the avalanche or streamer form (streamer corona). It is argued that heating of the streamer channel at its base gives rise to a region of highly ionized channel - plasma - with a very low longitudinal gradient. The formation of a highly conducting channel of limited length leads to a sharp increase in the field strength at the boundary of the plasma and to the appearance of a new streamer, which propagates in a different direction free from highly concentrated space charge introduced by the first streamer. Heating of the channel of the second streamer leads to further elongation of the conducting channel, which is called the leader. The continuous development of streamers one after the other ensures a continuous flow of electrons through the leader channel and the maintenance of a high temperature in the channel. The condition for breakdown of the gap is the condition for appearance of a leader. This is determined entirely by thermal processes in the streamer channel.

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137. (**)

AUTHORS	Kekez, M. M.; Savic, P.
TITLE	Laboratory Simulation of the Stepped Leader in Lightning
TYPE	journal
PAGE	2216-2224
JOURNAL	Canadian Journal of Physics
VOLUME	54
NUMBER	22
DATE	Nov. 15, 1976
KEYWORD	basic; experimental; simulation
LANGUAGE	English
ABSTRACT	It is shown that the 'stepped leader' often observed in lightning discharges is a manifestation of the nonlinear characteristic of the glow surrounding the leader tip, together with the parallel resistance-capacity behaviour of the far-field region. The resulting relaxation oscillations lead to intermittent discharges, which are simulated by adding resistance and capacitance to the external circuit of a standard discharge gap experiment. In addition, two complementary experiments were carried out to further illustrate that the stepped leader is subject to a continuous sequence of 'run-stop' conditions, whereby the fast transient displacement current is absent, is presented. This interpretation is largely confirmed by the present experiments as well as those of Ganger and Maier (1972).

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138. (**)

AUTHORS Kern, A.

TITLE Simulation and Measurement of Melting Effects on Metal Sheets Caused by Direct Lightning Strikes

TYPE report

SPONSOR National Aeronautics and Space Administration

NTIS N91-32644/7/XAB

DATE 1991

KEYWORD aircraft; review; simulation; simulation evaluation

LANGUAGE English

ABSTRACT Direct lightning strikes melt metal parts of various systems, like fuel and propellant tanks of rockets and airplanes, at the point of strike. Responsible for this melting are the impulse current and, if occurring, the long duration current, both carrying a remarkable charge Q. For studying these meltings the simulation in the laboratory has to be based on the parameters of natural lightning. International standards exist defining certain threat levels of natural lightning and giving possible generator circuits for the simulation. The melting caused by both types of lightning currents show different appearance. Their characteristics, their differences in melting and heating of metal sheets are investigated. Nevertheless the simulation of lightning in the laboratory is imperfect. While natural lightning is a discharge without a counter electrode, the simulation always demands a close counter electrode. The influence of this counter electrode is studied.

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139. (**)

AUTHORS Khaled, M.

TITLE Computation of Corona Onset Using the Ring-Charge Method

TYPE journal

PAGE 107-111

JOURNAL Proceedings of the IEE

VOLUME 122

NUMBER 1

DATE Jan. 1975

KEYWORD model; corona onset; electron avalanche; air breakdown

LANGUAGE English

ABSTRACT A new method of computing the corona-onset voltage in wire-plane systems is described. It is based on the principle that the positive ions, formed during the growth of the avalanche, are concentrated in circular rings located at places were ionization collisions are believed to occur, and the number of electrons at the avalanche head is doubled. Onset level is reached when the resultant electric field at the anode tip drops below a certain value. The method has been successfully applied to wire-plane configurations subjected to positive d.c. stress in atmospheric air. Results are in excellent agreement with those found in the literature.

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140. (**)

AUTHORS Khastgir, S. R.

TITLE Leader Stroke Current in a Lightning Discharge According to the Streamer Theory

TYPE journal

PAGE 616-617

JOURNAL Physical Review

VOLUME 106

NUMBER 4

DATE May 15, 1957

KEYWORD theory; lightning; streamer; velocity

LANGUAGE English

ABSTRACT In an earlier paper, Loeb calculated the current and fields down the axis of a streamer in a lightning discharge in relation to the streamer tip velocity and arrived at the concept of the expanding streamer channel to account for the observed breadth of the stepped leaders. Using illustrative data, he calculated the value of the current from the velocity of the streamer tip and arrived at a current of about 1200 amperes. In doing this, Loeb had tacitly ascribed the observed field-changes during the leader to the bright leader step. It is shown here that the field-changes observed cannot be ascribed to the fast step-flash but is caused by the slowly advancing pilot leader. The pilot-leader current can be calculated from Loeb's formula: $I=qv_t$, where q is the electrical charge carried by the pilot leader per cm and v_t the tip velocity of the streamer. If one assumes that 4 coulombs of charge reach the earth during the leader stroke, the length of the channel being taken as 5 km and taking $v_t=4\times10^7$ cm/sec, the pilot-leader current would be 320 amperes. The step-flash carries a much larger current, but since its duration is very small, the charge that flows during the step-flash is too feeble to produce observable stepped electrostatic field-changes during the stepped-leader process.

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141. (**)

AUTHORS Kitterman, C. G.

TITLE Characteristics of Lightning From Frontal System Thunderstorms

TYPE journal

PAGE 5503-5505

JOURNAL Journal of Geophysical Research

VOLUME 85

NUMBER C10

DATE Oct. 20, 1980

KEYWORD observations; streak camera; frontal system; lightning flash; multiple strokes; statistical distribution

LANGUAGE English

ABSTRACT A slowly rotating streak-camera array was used to photograph lightning flashes to ground from thunderstorms associated with 13 large frontal systems. Photographs of 139 flashes were obtained at Kansas City, Missouri, during 1979. Comparison of the frequency distributions of flash duration between frontal thunderstorms and air mass thunderstorms over nonmountainous terrain showed little difference between the two. However, comparison of the distributions of the number of strokes per flash indicated that frontal thunderstorms produce a greater percentage of high-order multiple stroke ground flashes than do air mass thunderstorms.

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142. (**)

AUTHORS Kline, L. E.

TITLE Corona Cloud Model Predictions of Switching Surge Flashover Voltages vs. Electrode Geometry

TYPE conference

PAGE F 76 345-9

CONFERENCE IEEE Power Engineering Society Summer Meeting, 1976

LOCATION Portland, Oregon

DATE July 18, 1976

KEYWORD model; corona; switching surge; electrode geometry; air breakdown

LANGUAGE English

ABSTRACT Calculated positive switching surge flashover voltages for a wide range of electrode geometries are presented and compared with experiment in this paper. The results are presented as flashover voltages relative to rod-plane gap flashover voltages, or gap factors. Calculated and experimental results are in good agreement. The theoretical model used assumes a conducting corona cloud with an experimentally observed shape. The calculations show that corona cloud growth becomes unstable when the corona cloud has crossed about two-thirds of the interelectrode gap. The simplicity of the corona cloud model and the use of the charge simulation method for the required electric field calculations permit flashover voltage estimates for complex, three-dimensional electrode geometries.

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143. (*)

AUTHORS Kline, L. E.

TITLE Monte Carlo Study of Ionization Zone Electron Kinetics in Negative Pin-Plane Coronas in Atmospheric Air

TYPE journal

PAGE 3715-3719

JOURNAL Journal of Applied Physics

VOLUME 58

NUMBER 10

DATE Nov. 15, 1985

KEYWORD model; corona; ionization; air

LANGUAGE English

ABSTRACT Monte Carlo simulation techniques are used to study the electron transport properties in the high electric field region near the pin in negative pin-plane corona discharges in atmospheric air. The results of the calculations show that the discharge electrons are nearly in equilibrium with the high local electric field near the pin tip. Consequently, a simpler computational model can be used to predict the voltage-current characteristics of these discharges. The results also show that ionization growth is very rapid for the pin-tip radii, gap lengths, and applied voltages which have been studied experimentally.

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144. (**)

AUTHORS Klingbeil, R.; Tidman, D. A.
TITLE Theory and Computer Model of the Lightning Stepped Leader
TYPE journal
PAGE 865-869
JOURNAL Journal of Geophysical Research
VOLUME 79
NUMBER 6
DATE Feb. 20, 1974
KEYWORD theory; lightning; stepped leader
LANGUAGE English
ABSTRACT A theory and a computer model of the lightning stepped leader are developed that include a pilot leader and an arc core. Step lengths, pause times, and other physical quantities are obtained that are in harmony with experimental observations.

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145. (**)

AUTHORS Kohrmann, W.
TITLE Influence of Water Vapor on the Electrical Breakdown of Air
TYPE journal
PAGE 379-384
JOURNAL Annalen der Physik
VOLUME 18
DATE 1956
KEYWORD experiment; air breakdown; water vapor
LANGUAGE German
ABSTRACT The purpose of this investigation is to understand the existing discrepancy between the statistical breakdown voltages of air. It is shown from measurements that the statistical breakdown voltage of air in a parallel plate spark gap depends on water vapor content. Additionally, from measurements of the formative time lag as a function of overvoltage, it is possible to gain insight into the discharge formation mechanisms. At small overvoltage a Townsend mechanism prevails involving photoelectron emission at the cathode; whereas at high overvoltage, streamer formation predominates. By the addition of water vapor, the boundary between these two mechanisms shifts to lower overvoltage.

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146. (*)

AUTHORS Krehbiel, P. R.; Brook, M.; McCrory, R. A.
TITLE An Analysis of the Charge Structure of Lightning Discharges to Ground
TYPE journal
PAGE 2432-2456
JOURNAL Journal of Geophysical Research
VOLUME 84
NUMBER C5
DATE May 20, 1979
KEYWORD measurement; lightning stroke; electric field; horizontal breakdown; charge

LANGUAGE English

ABSTRACT Sources of charge for the individual strokes of four multiple-stroke flashes to ground have been determined, using measurements of the electrostatic field change obtained at eight locations on the ground beneath the storm. The resulting charge locations have been compared to 3-cm radar measurements of precipitation structure in the storm. The field changes of individual strokes were found to be reasonably consistent with the lowering to ground of a localized or spherically symmetric charge in the cloud. The centers of charge for successive strokes of each flash developed over large horizontal distances within the cloud, up to 8 km, at more or less constant elevation between the -9 degree and -17 degree centigrade environmental (clear air) temperature levels. Comparison with the radar measurements has shown that the discharges developed through the full horizontal extent of the precipitating region of the storm and appeared to be selectively discharged regions where the precipitation echo was the strongest. Vertical extent of the stroke charge locations was small in comparison with the vertical extent of the storm. The field changes in the intervals between strokes have been found to exhibit many of the features which Malan and Schonland used to infer that ground flashes discharge a nearly vertical column of charge in the cloud. This and other evidence is used to show that their observations, which were made at a single station, could instead have been horizontally developing discharges. The interstroke field changes have been analyzed using a point dipole model and found to correspond to predominantly horizontal charge motion that was closely associated with the ground stroke sources for the flashes. The interstroke activity served effectively to transport negative charge in the direction of earlier strokes discharged in more distant regions of the cloud. Long-duration field changes that sometimes preceded the first stroke of a flash have been analyzed and found to correspond to a series of vertical and horizontal breakdown events within the cloud, prior to development of a leader to ground. These events were associated in part with the negative charge region that became the source of the first stroke and effectively transported negative charge away from the first stroke charge volume and from the charge volumes of subsequent strokes. Several continuing current discharges were found also to progress horizontally within the cloud and sustained currents in the range of 580 A to less than 50 A. The continuing current field changes were consistently better fitted by the monopole charge model than the field changes of discrete strokes within the same flash.

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147. (**)

AUTHORS Krider, E. P.

TITLE An Unusual Photograph of an Air Lightning Discharge

TYPE journal

PAGE 24-27

JOURNAL Weather

VOLUME 29

DATE 1974

KEYWORD observation; lightning

LANGUAGE English

ABSTRACT COMMENT: Photographic evidence is presented of a predominantly horizontal lightning event.

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148. (*)

AUTHORS Krider, E. P.; Musser, J. A.
TITLE Maxwell Currents Under Thunderstorms
TYPE journal
PAGE 11171-11176
JOURNAL Journal of Geophysical Research
VOLUME 87
NUMBER C13
DATE Dec. 20, 1982
KEYWORD basic; field; maxwell current; model
LANGUAGE English
ABSTRACT We point out that recent observations of the time variations in thunderstorm electric fields, both aloft and at the ground, can be interpreted in terms of a total Maxwell current density that varies slowly with time in the intervals between lightning discharges. We utilize this quasi-static behavior to estimate and map the Maxwell current densities under a small Florida thunderstorm using data provided by a large field mill network. An area integral of these current densities gives a total Maxwell current just above the ground of about 0.5 A, a value which is a reasonable lower limit for the total Maxwell current produced by the cloud, and an upper limit for the rate of charge transport to ground between lightning flashes. Using the quasi-static behavior of the Maxwell current density, we derive an expression for the field-dependent current density under a thunderstorm during the field recovery following a lightning discharge, and we infer values of air conductivity under the small storm which range from 2 to 6×10^{-13} mho/m. Finally, we present data that indicate that the area-average Maxwell current is not usually affected by lightning, but instead varies slowly throughout the evolution of the storm. Therefore, we suggest that cloud electrification processes probably do not depend on the cloud electric field, which exhibits large and rapid time variations, as much as they do on more slowly varying quantities, such as the meteorological structure of the storm and/or the storm dynamics.

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149. (***)

AUTHORS Kurilov, V. A.
TITLE Orientation of Lightning Discharges Towards Grounded Objects
TYPE journal
PAGE 24-30
JOURNAL Izvestiya Vysshikh Vchebnykh Zavedenii, Energetika
NUMBER 11
DATE Nov. 1979
KEYWORD experimental; model; streamer; theoretical
LANGUAGE Russian
ABSTRACT A theory of orientation of lightning discharges towards objects and structures is proposed. It is based on the idea that orientation of discharges is a consequence of development of electronic avalanches in the streamer zone of a leader head in the direction of field intensification. Data of natural observations and of experiments are compared with computational results obtained in accordance with the formulas presented. Their correspondence with the experimental results is much better than in the case of the formulas ordinarily used in calculating lightning hazards for tall objects.

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150. (**)

AUTHORS Laan, M.; Peeter, P.

TITLE The Multi-avalanche Nature of Streamer Formation in Inhomogeneous Fields

TYPE journal

PAGE 970-978

JOURNAL Journal of Physics D: Applied Physics

VOLUME 27

DATE 1994

KEYWORD streamers; air breakdown; corona; experiment; model; space charge

LANGUAGE English

ABSTRACT The streamer formation in a positive point-plane gap both in air and nitrogen has been studied. The primary electrons were created by laser radiation. This gave the opportunity to initiate streamers in a wide range of voltages including the range of a steady corona in air as well as to determine the formative time lags. A streamer starts when the space charge density reaches a critical value in a spatially localized region. In a divergent field the streamer formation is preceded by accumulation of space charge, i.e. it has a multi-avalanche nature. A model for calculation of formative time lags is presented. For a virgin gap the model describes fairly the accumulation process. For the voltage range of steady corona in air only the qualitative description of the mechanism is given.

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151. (***)

AUTHORS Large, M. I.; Pierce, E. T.

TITLE The Dependence of Point-Discharge Currents on Wind as Examined by a New Experimental Approach

TYPE journal

PAGE 251-257

JOURNAL Journal of Atmospheric and Terrestrial Physics

VOLUME 10

NUMBER 5/6

DATE 1957

KEYWORD experiment; point discharge; corona; wind; space charge; air breakdown; thunder cloud

LANGUAGE English

ABSTRACT Experiments are described in which a metal point mounted in the open air is artificially raised to a high potential V and the resulting point-discharge current I is measured. The relation $I=A(V-V_o)((W^2 + c^2V^2))^{1/2}$ where A and c are constants, W the wind speed, and V_o the onset potential, is found to fit the results reasonably well. It is shown that all point-discharge experiments may be interpreted in terms of the rapidity with which the ambient space-charge is removed; this removal may be by the wind or by the ion velocity in the surrounding field, and the relative importance of the two factors will vary from experiment to experiment. Finally, some remarks on the alti-electrograph results are appended.

COMMENT: This work shows the significant effect that wind can have on corona intensity around a sharp object and on the redistribution of space charge in the atmosphere. It is pointed out in this work that point current appeared to respond almost instantly to fluctuations in the wind speed. The experiments were performed in the natural environment.

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152. (**)

AUTHORS Larigaldie, S.; Labaune, G.; Moreau, J. P.
TITLE Lightning Leader Laboratory Simulation by Means of Rectilinear Surface Discharges
TYPE journal
PAGE 7114-7120
JOURNAL Journal of Applied Physics
VOLUME 52
NUMBER 12
DATE Dec. 1981
KEYWORD basic; experimental; simulation; theoretical
LANGUAGE English
ABSTRACT Gliding discharges over dielectric slabs can be made quasi-rectilinear by using a correctly shaped guiding electrode located behind the slab. Such guided discharges are characterized by the accessibility of their parameters to various diagnostic techniques, such as velocity, current and voltage measurements, spectroscopy, and fast photography. In this paper, the behavior of negative gliding-surface discharges is studied with a view of understanding the behavior of the lightning leader. Theoretical predictions obtained by computation from a simplified model are compared with experimental data, and the result of this comparison is discussed.

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153. (*)

AUTHORS Larigaldie, S.; Roussaud, A.; Jecko, B.
TITLE Mechanisms of High-Current Pulses in Lightning and Long-Spark Stepped Leaders
TYPE journal
PAGE 1729-1739
JOURNAL Journal of Applied Physics
VOLUME 72
NUMBER 5
DATE Sept. 1, 1992
KEYWORD aircraft; basic; field; model
LANGUAGE English
ABSTRACT The mechanisms of high-current transients in lightning stepped leaders and in long laboratory sparks at negative polarity are analyzed both from improved time resolution measurements and from systematic identifications of the various elements of the discharge during a pulse. A qualitative model was first constructed when the observations made were correlated with some previously known basic phenomena. Then the model was made qualitative by means of a computer simulation of spark formation, carried out from a modified program in electromagnetics. The relevance of the proposed model was checked for long sparks at negative polarity when computed and recorded current pulse wave forms were compared. Finally, the model of stepped-leader development was applied to a full scale event: an in-flight lightning strike on an instrumented aircraft. Slight discrepancies between computed and recorded current pulse wave forms may indicate possible underestimation of the electromagnetic high-frequency threat to sensitive airborne equipment due to the frequency limitations of the transient recorders used for lightning characterization on aircraft.

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154. (***)

AUTHORS Lee, R. H.

TITLE Protection Zone for Buildings Against Lightning Strokes Using Transmission Line Protection Practice

TYPE journal

PAGE 465-470

JOURNAL IEEE Transactions on Industry Applications

VOLUME IA-14

NUMBER 6

DATE Nov/Dec 1978

KEYWORD lightning protection; protection zone; transmission line; data analysis

LANGUAGE English

ABSTRACT The nature of the zone of protection of structures from an elevated rod or wire, inadequately defined in the past, can be determined with high reliability using data developed by E. R. Whitehead of the Illinois Institute of Technology under contract from the Edison Electric Institute for the protection of high-voltage electric transmission lines. The vertical boundary of this zone of protection is not linear, as has been believed in the past, but is a circular arc, tangent to the ground, of 150-ft radius for 99.5 percent protection and 125-ft radius for 99.9 percent protection.

COMMENT: The "rolling sphere" concept for defining a zone of protection was apparently first introduced in this paper.

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155. (**)

AUTHORS Lefort, L; Boilloz, P.; Lefort, M.; Lambin, B.

TITLE Method and Apparatus for Protection Against Lightning

TYPE US patent

DATE June 21, 1988

NTIS Patent no. 4,752,854

KEYWORD ESE device; electrically triggered; lightning protection

LANGUAGE English

ABSTRACT A method and apparatus is provided for protecting against lightning. An atmospheric potential tapping member is disposed for this purpose in the atmospheric field prone to lightning to collect a voltage (U_c) which, before there is a real threat of the lightning striking, has a value which remains within a lower voltage range (U_b) a capacitor is progressively charged with the voltage U_c and a few tens of microseconds before there is a real threat of the lightning striking at a given place, the atmospheric field will undergo a sudden increase and will therefore influence, relatively in the same way, the voltage collected which will rise up to and into a range (U_h) of voltages greater than that (U_b) where it was situated up to then. This potential gradient is detected with respect to time, and the evolution of the potential gradient (dv/dt) detected with respect to time is monitored in this upper range (U_h) of voltages.

When the potential gradient detected with respect to time rises beyond a predetermined threshold, the capacitor is caused to discharge into a discharge circuit.

COMMENT: This patent document describes the construction and operation of an electrically triggered ESE device that has evidently been incorporated into some commercially available lightning protection systems.

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156. (**)

AUTHORS	Leite, D. M.
TITLE	Experience of Radioactive Lightning Aerials in Field and in Laboratories
TYPE	conference
PAGE	127-133
CONFERENCE	Conference Proceedings. ICLP '85: 18th International Conference on Lightning Protection
LOCATION	Munich, Germany
SPONSOR	VDE-Verlag, Berlin, West Germany
DATE	Sept. 16, 1985
KEYWORD	field; radioactive rod; review
LANGUAGE	English
ABSTRACT	In Brazil there are thousands of installations protected by RLA (radioactive lightning aerials). Most of the RLA are installed in residential or commercial buildings of reinforced concrete where the probability of failures with serious consequences is very low. In many buildings the installation of the RLA is made according to the rules of the RLA and the radioactive material is considered just an extra help. The operating principles of radioactive lightning aerials are listed and the most important characteristics claimed by the manufacturers with the respective tests made in the laboratory in order to check them are given. Some of the failures of radioactive lightning aerials occurring in Brazil resulting from lightning in residential buildings, open areas, football fields, farms and alcohol distilleries are given.

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157. (***)

AUTHORS	Leoni, P.
TITLE	Radioactive Isotopes Do Not Improve Lightning Conductor Performance
TYPE	journal
PAGE	227-233
JOURNAL	Elettrificazione
NUMBER	5
DATE	May 1973
KEYWORD	critique; radioactive rod; review
LANGUAGE	Italian
ABSTRACT	The paper outlines the work of Franklin on lightning and his lightning conductor. It describes early work, such as the effect of discs of radioactive salts on atmospheric electrical discharges is outlined, followed by the effects of radioactivity on discharge current and discharge voltage. Research has shown that there is no useful application in the field of lightning protection, despite some laboratory success.

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158. (**)

AUTHORS	Liew, A. C.
TITLE	Lightning Damage and Problems Experienced in Some Structures/Systems in Singapore
TYPE	conference

PAGE 7.2/1-8
CONFERENCE Lightning Protection 92: Buildings, Structures and Electronic Equipment Conference and Exhibition
LOCATION Leatherhead, UK
SPONSOR ERA Technology
DATE June 23, 1992
KEYWORD field; radioactive rod; review
LANGUAGE English
ABSTRACT Singapore, which lies just one degree north of the equator, experiences very high lightning activity. Its isoceraunic level is about 180 thunderdays per year with a ground flash density of about 12.6 strokes per sq km per year. It comes as no surprise that building structures, widely spread complexes and systems are affected by lightning. The author documents some case histories of damages and problems experienced in the following: (1) a high rise building with standard external lightning protection which experiences flashovers within the building and damage to electrical equipment; (2) a petrochemical complex which suffered frequent damage to its process control computers, autogate cardkey systems, fire alarm systems, etc; and (3) buildings installed with radioactive lightning protection systems which have clearly experienced failures. The author also discusses the causes for the problems encountered and solutions or steps taken to improve their performance.

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159. (*)
AUTHORS Lin, Y. T.; Uman, M. A.; Standler, R. B.
TITLE Lightning Return Stroke Models
TYPE journal
PAGE 1571-1583
JOURNAL Journal of Geophysical Research
VOLUME 85
NUMBER C3
DATE March 20, 1980
KEYWORD basic; Bruce-Golde model; model; return stroke model; transmission line model
LANGUAGE English
ABSTRACT We test the two most commonly used lightning return stroke models, Bruce-Golde and transmission line, against subsequent stroke electric and magnetic field wave forms measured simultaneously at near and distant stations and show that these models are inadequate to describe the experimental data. We then propose a new return stroke model that is physically plausible and that yields good approximations to the measured two-station fields. Using the new model, we derive return stroke charge and current statistics for about 100 subsequent strokes.

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160. (**)
AUTHORS Lippert, J. R.
TITLE Evaluation of Rocket Triggered Lightning for Research and Development
TYPE report
SPONSOR Air Force Institute of Tech., Wright-Patterson AFB

NTIS AD-A100 548/7
DATE 1981
KEYWORD model; rocket; triggered
LANGUAGE English
ABSTRACT The feasibility of using rocket-triggered lightning as a research and development tool for testing hardware is investigated. Previous experimental work in the area is examined and used as the foundation for the experiments in this thesis to establish the significant factors of a successful lightning-triggering station. Using a point charge model, computer simulations were performed to determine the most probable locations of the charge centers associated with the triggered discharge. Five electric field records obtained from field mills were used to perform this simulation. A full scale test technique configuration is proposed for the subjecting representative Air Force subsystems and components to the lightning threat. A conclusion is drawn that such a system is feasible at Mt. Baldy, New Mexico with minor augmentations of the existing facilities of the Langmuir laboratory.

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161. (**)
AUTHORS Liu, X; Wang, C; Zhang, Y.; Xiao, Q; Wang, D; Zhou, Z.; Guo, C.
TITLE Experiment of Artificially Triggering Lightning in China
TYPE journal
PAGE 10727-10731
JOURNAL Journal of Geophysical Research
VOLUME 99
NUMBER D5
DATE May 20, 1994
KEYWORD triggered lightning; observations; rocket; model
LANGUAGE English
ABSTRACT Triggering lightning experiment with rocket-wire technique was conducted in Gansu, northwestern China. Ten cases of triggered lightning were obtained in three summers from 1989 to 1991. They were all with positive electric field at ground (positive charge overhead) under the influence of dominant lower positive charge of Gansu thundercloud. Triggered lightnings were weak discharges initiated by upward moving negative leaders followed by continuous current processes. No dart leader-return stroke processes were observed. The discharge lasted about several tens of milliseconds with a peak current of only a few hundred amperes. Simple physical models are used to evaluate the velocity of leader propagation, magnitudes, and altitudes of the charge transferred by triggered lightnings. Results are consistent with the features of lower positive charge of Gansu thunderstorms.

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162. (**)
AUTHORS Loeb, L. B.
TITLE Confirmation and Extension of a Proposed Mechanism of the Stepped Leader Lightning Stroke
TYPE journal
PAGE 5813-5817
JOURNAL Journal of Geophysical Research

VOLUME 73
NUMBER 18
DATE Sept. 15, 1978
KEYWORD theory; lightning; stepped leader; streamer
LANGUAGE English
ABSTRACT The postulated space wave of potential gradient, originating in an asymmetrical velocity of advance of positive and negative streamers and resulting from encounters of positive streamer tips with negative charge elements, has now been verified by Wagner in uniform field breakdown in the laboratory. This space wave constitutes the fast bright step that reactivates the pilot leader advance. Possible reflection at the end of the pilot streamer advance may account for the illumination of earlier steps reported by Berger and Vogelsanger and for resonances leading to step uniformity. Recent work by Koppitz and by Tholl concern the rapid thermalization of the arc channels estimated by Uman. They account for the millimeter-diameter core photographed by Orville and theoretically inferred by Uman, which also explains the streaks in time-resolved stroke photographs.

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163. (**)
AUTHORS Lowke, J. J.
TITLE Theory of Electrical Breakdown in Air - The Role of Metastable Oxygen Molecules
TYPE journal
PAGE 202-210
JOURNAL Journal of Physics D: Applied Physics
VOLUME 25
DATE 1992
KEYWORD streamer; model; metastable oxygen; air breakdown; corona; humidity
LANGUAGE English
ABSTRACT A theory is given of electrical breakdown in air for non-uniform electric fields. It is proposed that space-charge effects tend to make the electric field in the streamer column uniform at a value of E/N for which effective ionization and attachment rates are equal (E is the electric field and N the gas number density). It is also proposed that a-$^1\Sigma_g$ metastable states of molecular oxygen, produced in the pre-breakdown corona and streamer processes, have a dominant role in determining E/N in the streamer channel, because of their ability to detach electrons from molecular oxygen negative ions and thus reduce the effective attachment coefficient. Assuming an effective value of $\alpha/N = 10^{-22}$ cm^2 (α being the ionization coefficient) at E/N = 20 Td, predictions of breakdown fields in dry air and humid air are in fair agreement with experimental results for rod-rod breakdown with electrode spacings from 0.5 m to 2.5 m. The effect of the metastables is to reduce the breakdown field applicable to parallel electrodes by a factor of about 6. It is predicted that 1% water vapor in air increases breakdown fields by about 11%. A breakdown criterion is derived defining the critical E/N for breakdown in terms of electron transport coefficients and metastable rate constants.

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164. (*)

AUTHORS Lunev, V.
TITLE Luminous Balls in Siberia and the Far East: Phenomenology, Experiment, Hypothesis
TYPE journal
PAGE 256-274
JOURNAL Soviet Physics Journal
VOLUME 35
NUMBER 3
DATE May 1992
KEYWORD ball lightning; bibliography; experimental; simulation
LANGUAGE English
ABSTRACT The paper generalizes the result of studies at the Laboratory for Natural-Technogenetic Electromagnetic Systems at the Tomsk Polytechnic Institute and members of the Tomsk Group for Studies of Anomalous Phenomena in the Environment, which were carried out from 1983 to 1989. 'Luminous balls,' are taken to mean quasispherical formations in the atmosphere that radiate in the optical range of electromagnetic wavelengths and are identified as ball lightning, bolides, plasmoids, and exotic objects. A 100-year historical retrospective review is made of a series of phenomena observed by people in Siberia and the Far East in the surface layer of the atmosphere in the form of luminous balls, including events of 1908, 1984, 1985 and 1986, which have become known throughout the world. A description is given of attempts at experimental simulation of luminous balls under natural and laboratory conditions by means of various initiating factors: ultraviolet radiation, radio-frequency radiation, laser radiation, geodynamic stress, thermal stimulation, radio-wave excitation, and electrical discharge. Hypotheses explaining some of the properties of luminous balls are formulated and discussed.

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165. (***)

AUTHORS Mackerras, D.; Darveniza, M.; Liew, A. C.
TITLE Standard and Non-Standard Lightning Protection Methods
TYPE journal
PAGE 133-140
JOURNAL Journal of Electrical and Electronics Engineering, Australia
VOLUME 7
NUMBER 2
DATE June 1987
KEYWORD critique; early streamer emission; Franklin rod; ionization terminal
LANGUAGE English
ABSTRACT Methods for interception lightning protection of structures of the type recommended in national codes such as AS1768-1983, Lightning Protection, are referred to here as the standard method. In contrast, a number of methods of lightning protection have been proposed that are referred to here as non-standard in that they do not conform to a recognized code. These methods involve using specially designed air termination devices that create enhanced ionization of air, either by radioactive sources, or by special arrangements of electrodes. Some systems also use a special purpose downconductor in the form of a coaxial cable. A review of existing knowledge of the main characteristics of the lightning flash to ground, the physical processes during the final stages of the first leader stroke, and the factors that control the attachment of the lightning channel to a

particular point on the structure, lead to the conclusion that no practical amount of additional ionization, from whatever source, can be relied upon to affect the final lightning attachment process in any significant way.

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166. (*)

AUTHORS Maier, W. B. II.; Kadish, A.; Sutherland, C. D.; Robiscoe, R. T.
TITLE A Distributed Parameter Wire Model for Transient Electrical Discharges
TYPE journal
PAGE 7228-7239
JOURNAL Journal of Applied Physics
VOLUME 67
NUMBER 12
DATE June 15, 1990
KEYWORD model; path tortuosity; theoretical; threshold behavior
LANGUAGE English
ABSTRACT A model for freely propagating transient electrical discharges such as lightning and punch-through arcs, is developed in this paper. The authors describe the electromagnetic fields by Maxwell's equations and they represent the interaction of electric fields with the medium to produce current with an equation. They illustrate the properties of this model for small-diameter, guided, cylindrically symmetric discharges. Analytic, numerical, and approximate solutions are given for special cases. The model describes, in a new and comprehensive fashion, certain macroscopic discharge properties, such as threshold behavior, quenching and reignition, path tortuosity, discharge termination with nonzero charge density remaining along the discharge path, and other experimentally observed discharge phenomena. Fields, current densities, and charge densities are quantitatively determined from given boundary and initial conditions. They suggest that many macroscopic discharge properties are properly explained by the model as electromagnetic phenomena, and they discuss extensions of the model to include chemistry, principally ionization and recombination.

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167. (***)

AUTHORS Markovic, P. D.; Ristic, D.
TITLE Radioactive Lightning Rod with Gamma Sources and Radiation Problem of Individuals and Population
TYPE journal
PAGE 1331-1334
JOURNAL Tehnika
VOLUME 36
NUMBER 9
DATE 1981
KEYWORD experimental; field; radiation protection; radioactive rod
LANGUAGE Croatian
ABSTRACT Presents the results of measurements and estimations of exposure doses from radioactive lightning rods for persons exposed in inhabited and noninhabited places. The results indicate that radioactive lightning rods are safe to use. A cost/price analysis will be necessary to justify their use.

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168. (**)

AUTHORS Marode, E.

TITLE The Mechanism of Spark Breakdown in Air at Atmospheric Pressure Between a Positive Point and Plane. I. Experimental: Nature of the Streamer Track

TYPE journal

PAGE 2005-2015

JOURNAL Journal of Applied Physics

VOLUME 46

NUMBER 5

DATE May 1975

KEYWORD experiment; streamer; air breakdown; point-plane gap; temporal development; corona discharge

LANGUAGE English

ABSTRACT The behavior of a point to plane discharge has been analyzed electrically and optically for centimetric gaps in air at atmospheric pressure. This shows that for both steady and pulsed applied potentials the evolution always consists of the sequence: primary streamer, secondary streamer, dark space (more or less pronounced), transient arc. Experiments are presented that are directed towards obtaining an indication of the physical meaning of these different phases. A time-resolved spectroscopic analysis leads to an evaluation of the electron energy within the secondary streamer of ~1.4 eV. This indicates that the secondary streamer does not correspond to a very strong ionizing region. Three significant observations have been obtained using a device that is able to distinguish between conduction and displacement currents: (i) the secondary streamer occurs within a conducting filament built up by the primary streamer, (ii) when the primary streamer arrives at the plane, a cathode region appears giving continuity between the collected current at the plane and that flowing in the conducting filament, and (iii) there is a strong injection of negative charge into the gap from this cathode region. Finally, by varying the oxygen partial pressure, it is shown that the current within the discharge is mainly due to electrons. These results lead to a model of the discharge evolution in which the filament track of the primary streamer can be considered as a transient positive column of a glow discharge, whose cathode region is formed when the primary streamer arrives at the cathode. The secondary streamer thus appears to be the luminosity of a positive column.

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169. (**)

AUTHORS Marode, E.

TITLE The Mechanism of Spark Breakdown in Air at Atmospheric Pressure Between a Positive Point and Plane. II. Theoretical: Computer Simulation of the Streamer Track

TYPE journal

PAGE 2016-2020

JOURNAL Journal of Applied Physics

VOLUME 46

NUMBER 5

DATE May 1975

KEYWORD theory; streamer; air breakdown

LANGUAGE English

ABSTRACT Based on a model which was experimentally established, a numerical simulation is presented of the spatiotemporal evolution of electron density, current, and electrical field in the filamentary streamer track. The attachment process is taken into account in the continuity equation for electrons and the Poisson's equation is simplified using a coefficient of capacity per unit length. Boundary conditions for the filament are deduced (i) from the experimental measurements on the primary streamer and (ii) by assuming a constant cathode fall for the experimentally found cathode region. The results show good agreement between calculation and experiment for both currents and streak photograph.

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170. (*)

AUTHORS Mazur, V.
TITLE Lightning Channel Properties Determined with a Vertically Pointing Doppler Radar
TYPE journal
PAGE 6165-6174
JOURNAL Journal of Geophysical Research
NUMBER D4
DATE June 30, 1985
KEYWORD basic; experimental; field; plasma channel
LANGUAGE English
ABSTRACT Measurements of lightning have been made with a vertically pointing, 10 cm wavelength Doppler radar and have shown that the lightning echoes produce identifiable coherent peaks in the Doppler spectrum. The evolution of intensity and position of the spectral peaks in the velocity domain are used to infer some channel properties. From analysis of 40 lightning echoes, all of them produced by intracloud flashes, it was determined that (1) the ionized lightning channels remain overdense for 25-200 ms; (2) the decay of the lightning channel radar cross section is exponential; and (3) lightning channels are accelerated most probably by a combination of buoyancy and the Earth's magnetic field acting on the hot plasma channel through which a current flows. The resulting channel velocity is apparently due to accelerations from these forces combined with the velocity of the air in which the lightning is embedded.

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171. (**)

AUTHORS McAllister, I. W.; Crichton, C. G.; Bregnsbo, E.
TITLE Experimental Study on the Onset of Positive Corona in Atmospheric Air
TYPE journal
PAGE 6797-6805
JOURNAL Journal of Applied Physics
VOLUME 50
NUMBER 11
DATE Nov. 1979
KEYWORD experimental; corona onset; streamers; air breakdown; electrode geometry
LANGUAGE English
ABSTRACT This paper reports the findings of a study into the gas physical processes which lead to the inception of the positive corona discharge in atmospheric air. A multiple avalanche

process is observed to be a basic feature, and correlation with works reported in the literature suggests that at corona onset the physical phenomena are independent of electrode radius of curvature ρ in the range $0.04 < \rho(mm) < 250$. The various models used to simulate the precorona discharge sequence and to predict corona-onset field-strength values are then examined. It is concluded that the development of a rigorous physical-mathematical model of corona onset must await a full understanding of the avalanche-to-corona transition mechanism. Prior to this, a simple empirical approach is adequate for the prediction of corona-onset field strengths.

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172. (**)

AUTHORS McAllister, I. W.; Pedersen, A.
TITLE Corona-Onset Field-Strength Calculations and the Equivalent Radius Concept
TYPE journal
PAGE 43-48
JOURNAL Archiv fur Elektrotechnik
VOLUME 64
DATE 1981
KEYWORD theory; corona onset; electrode geometry
LANGUAGE English
ABSTRACT The concept of the equivalent radius is examined in relation to its application to the evaluation of corona-onset field-strengths in atmospheric air. It is shown that the use of this concept provides erroneous values. The underlying reasons for this situation are discussed in detail, such that the basis for a physically meaningful approach to corona onset calculations is established.

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173. (**)

AUTHORS McEachron, K. B.
TITLE Lightning to the Empire State Building
TYPE journal
PAGE 149-217
JOURNAL Journal of the Franklin Institute
VOLUME 227
NUMBER 2
DATE February 1939
KEYWORD observations; lightning; photography, oscillographic records; current
LANGUAGE English
ABSTRACT Oscillograms and/or moving film Boys camera photographs have been taken of 55 strokes to the Empire State Building. Direct current arcs, with or without superimposed current peaks, extending between the cloud and the building continuing as long as 0.4 second, have been measured. These we have called continuing strokes. Upward leaders from the building which developed into continuing strokes have been photographed and data as to velocity of propagation secured. (Upward leader velocities range between 0.17 ft./microsecond and 2.09 ft./microsecond with an average of 0.84 ft./microsecond). Currents measured during build-up of upward stepped leaders range from 50 to 650 amperes. Branching was found to be in the direction of propagation of initial leader

strokes. At least 50 per cent of the strokes had a charge of 35 coulombs or more with a maximum of 164. These values are several times as large as heretofore believed probable. All strokes to the building began with the cloud negative. 3 strokes changed to positive at or near the end of the stroke. About 3 per cent of the total charge measured was associated with the positive portion of the strokes. Downward stepped leaders to the building were observed in one case only which had a velocity of 14 ft./microsecond. A stroke to a building 200 ft. in height had a downward stepped leader velocity of 5 ft./microsecond. Leaders on all discharges after the first were always downward whenever found, whether the initial leader was upward or downward. Such downward leaders had velocities ranging from 1.9 ft./microsecond to 128 ft./microsecond with an average of 39 ft./microsecond. Return stroke velocities following initial stepped downward leaders were 340 ft./microsecond and 150 ft./microsecond in the two cases recorded, while the return stroke velocities following continuous leaders ranged from 98 ft./microsecond to 280 ft./microsecond with an average of 197 ft./microsecond. Every stroke, but two, of which the author has a record, either struck the highest point on the building or outside a cone whose base radius at the ground level of the building was equal to the building height.

COMMENT: The results reported in this paper suggest that about 4% of the observed lightning strikes to the building fall outside of the "cone-of-protection."

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174. (**)

AUTHORS McEachron, K. B.

TITLE Lightning to the Empire State Building

TYPE journal

PAGE 885-889

JOURNAL Transactions of the American Institute of Electrical Engineers

VOLUME 60

DATE September 1941

KEYWORD observations; lightning; current measurements; statistics

LANGUAGE English

ABSTRACT

Lightning to the Empire State Building in New York City has been under investigation since 1935. Boys camera photographs of 62 strokes have been taken and 99 oscillograms. Twenty of these were taken simultaneously with photographs of the same stroke. Upward step leaders were discovered and continuing strokes were shown to be in the nature of a direct current arc. A brief resume of the more important results up to the end of the 1937 season is given.

The paper is chiefly concerned with the oscillographic results of the 1938 and 1940 seasons. The low speed oscillograph in the Empire State Building recorded 17 of the 20 strokes to the building while the high speed oscillograph recorded 41 current peaks in 13 strokes.

1. Of 49 strokes recorded oscillographically during the years 1937-40, no stroke has been entirely positive although 41, or 84 per cent, were entirely negative. The first recorded current peak in stroke 13 was positive and had a crest current of 58,000 amperes.

2. Fifty per cent of the 49 strokes had charge of 25 coulombs or more, the maximum charge measured being 164 coulombs. These values are for the total stroke and not for current peaks.

3. Ninety-one per cent of all the strokes recorded to the Empire State Building are classified as continuing, i.e. had a low current component.

4. Fifty per cent of the current peaks were found to have a crest current of 7,000 amp or more, while only 25 per cent of the 33 peaks measured in 11 strokes had a duration exceeding 40 microseconds.

5. The plotted data show that 50 per cent of the current peaks had a charge of 0.13 coulomb or more to half current value, although 5 per cent showed more that 1.5 coulombs.

6. A time of at least 1 microsecond is required to reach crest in 50 per cent of the current peaks, while 65 per cent reach the first crest in a time not greater than 1.5 microseconds-the time to crest of the present standard.

7. The results obtained show that rates of rise of the order 10 to 20 kiloamperes per microsecond will be encountered quite frequently, and 30 to 40 kiloamperes per microsecond occasionally.

8. Errors as great as ±50 per cent may occur in connection with the highest rate of rise measurements; errors in connection with some of the other measurements may be as great as ± 25 per cent, although most of the results will be more accurate than indicated by these values.

9. It is pointed out that direct stroke data may be applied to transmission and distribution circuits if proper allowances are made for division of currents in the various paths including the effect of grounded neutral transformers. The current to be handled by lightning arresters will in general be much smaller than those measured in the direct stroke.

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175. (**)

AUTHORS	McRae, B. P.; Diesendorf, J. L.; Glasson, G. T.
TITLE	A New Theory of Shielding Against Direct Lightning Strokes Based on Recent Lightning Discharge Data
TYPE	conference
PAGE	108-111
CONFERENCE	5th International Conference on Gas Discharges
LOCATION	Liverpool, UK
DATE	Sept. 11, 1978
KEYWORD	basic; model; theoretical
LANGUAGE	English
ABSTRACT	Negative downward lightning flashes which determine shielding performance are initiated by a stepped leader stroke which establishes a plasma channel between cloud and ground. The final strike distance is determined from the leader head charge as the

sum of the corona burst radius and the breakdown distance. The head charge is estimated from typical stroke waveshapes and recent statistical data on stroke current amplitudes and rise times. A computer program considers the last few steps of descent of each leader stroke to obtain the spatial distribution of leader head locations from which the final strike may be made in any direction.

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176. (**)

AUTHORS Meek, J. M.
TITLE A Theory of Spark Discharge
TYPE journal
PAGE 722-728
JOURNAL Physical Review
VOLUME 57
DATE April 15, 1940
KEYWORD streamers; model; theory; air breakdown
LANGUAGE English
ABSTRACT The breakdown of a uniform field is considered to occur by the transition of an electron avalanche proceeding from cathode to anode into a self-propagating streamer, which develops from anode to cathode to form a conducting filament between the electrodes. A criterion is put forward for such a transition, viz., a streamer will develop when the radial field about the positive space charge in an electron avalanche attains a value of the order of the external applied field. For then photoelectrons in the immediate vicinity of the avalanche will be drawn into the stem of the avalanche and will give rise to a conducting filament of plasma, and a self-propagating streamer proceeds towards the cathode. The theory thus depends on ionization by electrons and photo-ionization in the gas and dispenses with the classical assumption of ionization by positive ions in the gas or secondary actions at the cathode. On this basis, an equation for breakdown is developed, and reference to α/P - E/P curves enables the potential required for breakdown to be determined. Satisfactory agreement between calculation and experiment is found in air for values of pressure times gap length (pd) down to about 100 mm Hg×cm. The theory does not conform absolutely to Paschen's law, but the deviations are within the present day margins of experimental error. For lower values of pd, the deviation between calculation and experiment is explained by the fact that the density of photo-ionization becomes small, and the secondary mechanism, gamma, is observed in this region, so that classical theory applies. The theory is indicated to be consistent with all the requirements so far established in connection with sparks for large pd up to lightning discharge.

COMMENT: It is significant to note that in this work the mechanisms for streamer discharge initiation and propagation were postulated for the first time.

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177. (**)

AUTHORS Menes, M.; Fisher, L. H.
TITLE Positive Point-to-Plane Corona Studies in Air
TYPE journal
PAGE 1-6

JOURNAL	The Physical Review
VOLUME	94
NUMBER	1
DATE	April 1, 1954
KEYWORD	experiment; corona; air; formative time lag; streamer
LANGUAGE	English
ABSTRACT	Formative time lags for the development of the positive point-to-plane corona in dry air were measured oscillographically at pressures ranging from atmospheric to a few centimeters of Hg. Studies with a photomultiplier tube show that the formative lags are associated with a filamentary streamer type of corona. These corona formative lags are of the order of 10^{-7} sec even near threshold and vary much more slowly with overvoltage than do uniform field formative lags in air. The results indicate that no long buildup process is associated with the formation of the filamentary streamer type of corona in air, and in particular rule out any cathode secondary mechanism from playing a role in the formation. Near atmospheric pressure, with the experimental conditions used, the corona formative time lags were often too short to be resolved from the statistical scatter; when resolvable they were found to be too long to be ascribed solely to a single transit time of the initiating electron avalanche across the high field region of the gap. The results therefore do not preclude a fast buildup process in the gas preceding streamer formation. Threshold measurements on both impulse and dc corona indicate that the steady glow type of corona has a different threshold than the streamer type. No formative lag data on the steady glow corona were obtained.

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178. (*)

AUTHORS	Miki, M.; Aihara, Y.; Shindo, T.
TITLE	Development of Long Gap Discharges Guided by a Pulsed CO_2 Laser
TYPE	journal
PAGE	1244-1252
JOURNAL	Journal of Physics D (Applied Physics)
VOLUME	26
NUMBER	8
DATE	Aug. 14, 1993
KEYWORD	experimental; guided; laser; pulse power
LANGUAGE	English
ABSTRACT	The mechanism of the guidance effect of laser plasmas on electrical discharges has been studied. A 45-J CO_2 laser pulse produces many spherical plasmas over a gap of up to 2 m, and the laser-guided discharge is formed along the plasma by the application of a lightning impulse voltage. Unusual properties of the laser guided discharge are obtained from streak photographs of the discharge development. The laser produced plasmas guide streamers and leaders from a negative electrode more effectively than from a positive electrode. The discharge development from the negative electrode plays an important role in the guidance effect.

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179. (**)

AUTHORS Mikropoulos, P. N.; Stassinopoulos, C. A.

TITLE Influence of Humidity on the Breakdown Mechanism of Medium Length Rod-Plane Gaps Stressed by Positive Impulse Voltages

TYPE journal

PAGE 407-417

JOURNAL IEE Proceedings - Science an Measurement Technology

VOLUME 141

NUMBER 5

DATE Sept. 1994

KEYWORD experiment; impulse breakdown; air; humidity effect; rod-plane gaps; corona; time to breakdown

LANGUAGE English

ABSTRACT To better understand the influence of atmospheric humidity on the breakdown mechanism of medium length rod-plane gaps when stressed by positive impulse voltages, emphasis was given to the initial prebreakdown phenomena (the first and second coronas) as well as the dark period. The salient events have been measured and assessed to determine the influence of humidity on breakdown probability curves, on the 50% breakdown voltages and on the distribution of the times to breakdown. During this investigation the main parameters, in addition to humidity, were the gap length, the geometry of the end of the rod and the front duration of the impulse voltage. Humidity was found to have a great influence on the breakdown mechanism, especially its streamer region. It influences not only the 50% breakdown voltage but also its standard deviation. It was also found to cause changes in the shape of the U-curves. The necessary correction for humidity was found to vary considerably with the front duration of the applied impulse.

COMMENT: This paper provides experimental evidence for the significant effect that atmospheric humidity can have on the initiation of a positive streamer under impulse conditions that might be similar to those encountered for negative lightning.

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180. (***)

AUTHORS Moghissi, A. A.; Paras, P.; Carter, M. W.; Barker, R. F.

TITLE Radioactivity in Consumer Products

TYPE report

SPONSOR Nuclear Regulatory Commission

NTIS PB-288 743/8

DATE 1978

KEYWORD radioactive rods; review

LANGUAGE English

ABSTRACT This book is based on papers presented at the symposium. Topics covered include: Regulations and standards; general and biological risks; radioluminous materials; mining, agricultural, and construction materials containing radioactivity; products containing radioactive sources; miscellaneous products.

COMMENT: This report contains three contributions from different authors about radioactive lightning rods. These contributions are listed below and also appear separately under the principal author's name in the present bibliography.

1) Title - Public Health Aspects in the Use of Radium-226 and Americium-241 in Lightning Rods, Authors - M. Belli, P. Salvadori, E. Sgrilli, and A. Susanna

2) Title - Nuclear Lightning Protection and the New Coaxial Lightning Protection System, Authors - J. R. Gumley, C. G. Invernizzi, M. Khaled, and C. W. Wallhausen

3) Title - Radioactive Lightning Rods, Static Eliminators, and Other Radioactive Devices, Authors - E. Fornes and P. Ortiz

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181. (***)

AUTHORS Moore, C. B.
TITLE Improved Configurations of Lightning Rods and Air Terminals
TYPE journal
PAGE 61-85
JOURNAL Journal of the Franklin Institute
VOLUME 315
NUMBER 1
DATE Jan. 1983
KEYWORD lightning rods; review; theory; design
LANGUAGE English
ABSTRACT

Franklin invented lightning rods with the hope that they would dissipate thunderstorm electricity and thus prevent lightning from striking. His invention was based on his findings that sharpened metal needles would allow electricity to flow silently through the air, away from highly charged objects. When his rods were used, however, instead of preventing lightning, they were sometimes "struck" and became part of a lightning path to ground. An analysis of the physics involved suggests that:
a) The flow of electricity from sharpened conductors at the earth's surface does not dissipate thunderstorm electricity sufficiently to prevent lightning.
b) The ionization and point discharges around the tip of a sharpened lightning rod limit the strength of the local electric field and reduce the probability of a lightning strike to the rod. The sharpened rod thus acts to protect itself against lightning discharges, but its protection does not extend to other objects in its vicinity. While a sharpened rod does not provide a preferred lightning path to earth, it can be used if no better paths are available.
c) Elevated, blunt rods or horizontal conductors, suitably connected to earth, can provide better lightning paths to earth and therefore, better protection to structures in their vicinity than do sharpened rods.
d) The connections from elevated conductors to earth need to be the most direct possible, with no abrupt changes in direction; impedance discontinuities created in down conductors at sharp bends cause reflections of lightning transients and may produce side flashes to other objects in their vicinity.

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182. (**)

AUTHORS Moore, C. B.

TITLE Preliminary Report on the 1993 Exposure of Commercial ESE Air Terminals on South Baldy Peak in New Mexico

TYPE report

PUBLISHER Moore, C. B. New Mexico Tech, Langmuir Laboratory, Soccoro, New Mexico 87801

DATE 1993

KEYWORD observations; air terminals; lightning strikes; ESE

LANGUAGE English

ABSTRACT COMMENT: This is a unreviewed report prepared at a university (New Mexico Tech) on results from observations and tests made on early streamer emission terminals in the natural environment. The following summary is given in the report: "Our findings with the magnetic tapes indicate that none of the 'early emission' air terminals were struck by significant lightning during three weeks of exposure to thunderclouds despite strikes around South Baldy in that period. Examination of the terminals at the end of the test suggests that none of them were exposed to high currents at any time earlier in the summer although lightning struck trees on the summit during the test. Our study thus far indicates that these unconventional devices are ineffective in providing lightning protection to structures in their vicinity while they seem quite able to protect themselves."

NOTE: The original title of this report contained references to specific commercial devices by trade name which have been deleted.

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183. (**)

AUTHORS Moore, C. B.; Mathis, J. A.; Rison, W.

TITLE Report on the Exposure of Eighteen Air Terminals Along the Crest of the Magdalena Mountains in New Mexico During the 1994 Thunderstorm Season

TYPE report

PUBLISHER Moore, C. B. New Mexico Tech, Langmuir Laboratory, Socorro, NM 87801

DATE 1994

KEYWORD observations; outdoor tests; lightning; air terminals; geometry; ESE

LANGUAGE English

ABSTRACT COMMENT: This is an unreviewed report prepared at a university (New Mexico Tech) on tests that were performed in 1994 of lightning strikes to or around several different air terminals positioned on a mountain in New Mexico where there are known to be frequent lightning strikes. Among the terminals tested were conventional devices (blunt rods) and ESE-type devices obtained from different manufacturers. Video recordings of several lightning strikes were made. They report evidence of at least one lightning strike that failed to hit a radioactive air terminal and struck the ground within the supposed range of protection of this device. The following general remarks from this report are worth noting:

"It is remarkable that not one of the eighteen air terminals was struck by natural lightning during their 1994 exposure despite our recording of more than 1000 discharges over the Magdalena mountain area."

"In our opinion, Franklin's idea that lightning rods should have sharp tips for easy ionization of the air is flawed and the basis for all similar terminal designs is wrong. It is not surprising therefore that none of the sharp-tipped air terminals that we have studied during the past 5 summers have ever been struck by lightning although objects in their vicinity have been struck many times."

"At the present time, there is no generally accepted understanding of how lightning rods and air terminals respond at the onset of lightning. As a result, there is no firm scientific basis for the design of any of the existing air terminals. For any real improvement in lightning protection, an understanding of the underlying physics is essential and we think that a greater effort should now be directed toward obtaining the knowledge necessary."

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184. (**)

AUTHORS	Morgan, C. G.
TITLE	Irradiation and Time Lags
TYPE	book
PAGE	655-688
BOOK	Electrical Breakdown of Gases, Edited by J. M. Meek and J. D. Craggs
PUBLISHER	John Wiley & Sons, Ltd., New York, NY
DATE	1978
KEYWORD	review; electrical breakdown; time lags; radiation; water vapor effect; air
LANGUAGE	English
ABSTRACT	COMMENT: This article presents a review of work conducted up to 1978 on investigation of time lags associated with electrical breakdown of gases including air. Considered in this article are the effects of radiation, electrode surface condition, and humidity. The following general statements are made respectively concerning the effects of radiation and humidity: 1) "The statistical time lag can practically be reduced to zero by illumination of the cathode by strong ultraviolet or soft x- and alpha-irradiation." 2) "It has been known since Faraday's early researches that the presence of water vapor in discharge gaps greatly facilitates the passage of sparks, i.e. reduces the statistical time lag. ... This enormous reduction indicates the role played by electrons detached from water molecules in initiating the discharges." Numerous references to earlier work are included.

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185. (**)

AUTHORS	Mousa, A. M.
TITLE	Effect of Height of Structure on the Striking Distance of a Downward Lightning Flash
TYPE	conference
PAGE	9-14
CONFERENCE	Proceedings of International Communications & Energy Conference
LOCATION	Montreal, Quebec

SPONSOR IEEE Publication No. CH20412
DATE Oct. 1, 1994
KEYWORD model; lightning protection; tall towers
LANGUAGE English
ABSTRACT Photographs of lightning strikes to tall towers frequently exhibit the following phenomena:

1. The striking distances appear to significantly exceed the calculated values.

2. The struck points are located far below the tower top.

3. The orientation of the striking distance is almost horizontal.

This paper explains the above phenomena. It is theorized that the observed excessive striking distances are due to an interaction between a downward lightning flash and the remnants of prior upward flash. The other two phenomena are shown to be due to the effect of height of structure on the shape of the shielding locus. A definition of the effective height is also proposed.

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186. (**)
AUTHORS Mousa, A. M.; Srivastava, K. D.
TITLE Shielding of Tall Structures Against Direct Lightning Strokes
TYPE conference
PAGE 342-352
CONFERENCE Canadian Conference on Electrical and Computer Engineering
LOCATION Vancouver, B.C., Canada
DATE Nov. 3, 1988
KEYWORD model; building; design; lightning protection
LANGUAGE English
ABSTRACT Tall structures are frequently struck by lightning at points far below the top of the structure, thus indicating the inadequacy of roof-installed lightning protection systems. This phenomenon is explained herein using the electrogeometric model theory. Revised lightning protection schemes are suggested and the governing analytical relations are presented and discussed.

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187. (***)
AUTHORS Muller-Hillebrand, D.
TITLE Change in the Path of Lightning by Ionizing Radiation and Space Charges
TYPE journal
PAGE 152-157
JOURNAL Elektronische Zeitschrifte Ausgabe A
VOLUME 83
DATE 1962
KEYWORD critique; ionizing terminal; review

LANGUAGE German

ABSTRACT The electrostatic field strength near and below a thundercloud is seldom higher on the ground than 10 kV/m and often only 3 kV/m for lightning strokes within 100 m distance of the measuring point. This is due to the space charges which originate as corona discharges from all points in the region. The space charges which are emitted from a high point can influence the path of lightning. To answer experimentally the question whether radio-active points of differing strength influence the corona current, measurements were carried out in electric fields of differing strength. In the laboratory no difference could be established between points with or without radium activation. But in the open, the corona current of the point(rod) with radium was always smaller than the current of the non-activated rods. This is due to an ion veil retarding with increasing field strength the onset of the corona discharge. Experimentally it was shown that corona currents up to 8 mA strongly alter the electric field over a wide range from the source of origin. The experimental proof that a lightning discharge could thus be influenced over several 100 m distance unfortunately failed in the summer of 1961.

Corona discharges which are emitted from high points can influence the path of lightning. The emission currents of radio-active lightning conductors are, however, much too weak to produce the space charges required for such an effect. A summary in English is included.

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188. (**)

AUTHORS Muller-Hillebrand, D.

TITLE The Protection of Houses by Lightning Conductors - An Historical Review

TYPE journal

PAGE 34-54

JOURNAL Journal of The Franklin Institute

VOLUME 274

DATE 1962

KEYWORD review; lightning protection; lightning conductor; houses

LANGUAGE English

ABSTRACT A review of the research work on lightning conductors is presented, from 1750 through 1960. On the basis of recent work, it is concluded that small houses may be economically protected from lightning damage.

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189. (**)

AUTHORS Murakami, A.

TITLE Lightning Protection Zones for Rocket Launch Complexes

TYPE report

SPONSOR Air Force

NTIS AP-P002 177/4

DATE 1993

KEYWORD model; protection zones; theoretical

LANGUAGE English

ABSTRACT This paper examines the Rolling Ball Theory for lightning protection zones. It provides support for this theory in terms of the critical gradient time history for lightning rods as described mathematically in terms of a prolate spheroid. The analysis show how the critical threshold gradient for a sharp object lying below a lightning rod can emit a ground streamer which will move above the lightning rod before the critical gradient is reached on the taller rod. This occurs only if the radius of the lightning rod tip is substantially larger than the radius of objects lying within its zone of protection and this results in defeat of the rod. Also considered is the use of the catenary cable protection system over launch complexes and the need for it.

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190. (*)

AUTHORS Nakamura, K.; Horii, K.; Aiba, S.
TITLE Discharge Currents in the Experiment of Artificially Triggered Lightning for Winter Thunderclouds
TYPE conference
PAGE 664-669
CONFERENCE 1989 International Symposium on Electromagnetic Compatibility
LOCATION Nagoya, Japan
SPONSOR IEEE (cat. no. 89TH0276-6, IEEE Service Center, Piscataway, NJ)
DATE Sept. 8, 1989
KEYWORD experimental; field; rocket; triggered; upward leader
LANGUAGE English
ABSTRACT An experiment involving the rocket-triggering of lightning has been carried out in Japan. Ninety-four strikes were obtained within eleven seasons from 1977 to 1988. The measuring results are presented, and discharge current and optical observations are discussed. The predischarge process was found to continue for one or two seconds before the beginning of the main discharge. The predischarge current started from a small current of milliampere order, and many pulse currents of ampere order appeared and increased with the ascent of the rocket. The leader current followed. The rate-of-rise of the positive current corresponding to the negative upward leader for a positive cloud was about ten times greater than that of the negative current to the upward leader for a negative cloud. The difference is due to the propagation-velocity difference between the leaders.

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191. (*)

AUTHORS Nakamura, K; Suzuki, T.; Yamabe, C.; Horii, K.
TITLE Fundamental Research for Lightning Trigger Experiment by Using UV Lasers
TYPE journal
PAGE 1265-1273
JOURNAL Trans. of the Institute of Electrical Engineers of Japan, Part B
VOLUME 113
NUMBER 11
DATE Nov. 1993
KEYWORD experimental; laser; triggered; ultraviolet
LANGUAGE Japanese

ABSTRACT This study was carried out to examine the possibility of lightning control using a photoionized plasma produced by a UV laser without an optical air breakdown. As its fundamental experiment, the characteristics of a laser-triggered spark gap (LTSG) were examined, where a laser beam was not irradiated on the surface of the electrodes. In this experiment, the KrF excimer laser was very effective for increasing the plasma density (n) and the reduction ratio (P) of 50% breakdown voltage against the self-breakdown voltage. The relation between n and P was explained by the streamer theory, and the reduction ratio P was increased by generating a long and high density plasma parallel to the discharge axis. On the other hand, the abnormal discharge process in triggered lightning using a rocket was examined, and it was indicated that the most important condition to trigger a lightning discharge was the production of a plasma channel whose length was 200 m and density was about $1/(10^{19})^3$. It was suggested that such a plasma channel could be produced by a KrF excimer laser with an energy of only about 3.67 J.

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192. (**)

AUTHORS Nasser, E.; Heiszler, M.
TITLE Mathematical-Physical Model of the Streamer in Nonuniform Fields
TYPE journal
PAGE 3396-3401
JOURNAL Journal of Applied Physics
VOLUME 45
NUMBER 8
DATE August 1994
KEYWORD streamer; model; nonuniform field
LANGUAGE English
ABSTRACT The initial electron avalanche created in the high nonuniform fields near an anode leaves behind it a space charge of positive ions that enhance the field farther away from the anode and, hence, produce the necessary conditions for successive electron avalanches to produce the streamer. A mathematical model of these processes has been derived and the minimum anode voltage required to satisfy these equations has been computed for different geometrical parameters. The streamer onset voltage agrees well with measured values. The conditions for streamer onset are found to exist whenever the average gradient of the field is higher than a certain value specified by the initial avalanche length.

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193. (**)

AUTHORS Newman, M. M.; Stahmann, J. R.; Robb, J. D.
TITLE Experimental Study of Triggered Natural Lightning Discharges
TYPE report
SPONSOR Federal Aviation Administration, Project No. 520-002-03X
NTIS Report. No. DS-67-3
DATE 1967
KEYWORD experiments; triggered lightning; photographic observations
LANGUAGE English

ABSTRACT Studies of natural lightning discharge channel have been continued in the summer of 1966 using a triggering technique during which 17 strokes were triggered out of 23 attempts. The discharges were triggered by firing a rocket carrying a fine wire to an altitude of about 400 meters when electric field meters indicated a discharge was probable. The studies showed clearly in the Fastax photographs, the current oscillograms, and in the still photographs the existence of a low current continuing component lasting up to 0.8 seconds following nearly every initial high current stroke. Also, high current restrikes were found after nearly every stroke with as many as a dozen restrikes in a single lightning discharge. Blast pressure measurements showed higher peak pressures than measured previously from triggered natural lightning discharges and also longer durations. This is of interest in relation to possible structural damage to aircraft and also in relation to shock wave effects on flame propagation in aircraft fuel vents. High speed motion pictures of the discharge clearly showed the violent snake like motion of the channel of importance in evaluation of stroke sweeping effects near aircraft.

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194. (*)

AUTHORS Niemeyer, L.
TITLE A Stepped Leader Random Walk Model
TYPE journal
PAGE 897-906
JOURNAL Journal of Physics D: Applied Physics
VOLUME 20
DATE 1987
KEYWORD model; leader propagation; stochastic behavior
LANGUAGE English
ABSTRACT A model is proposed which describes the statistical aspects of the geometric trajectories along which stepped leaders in electronegative gases cross a discharge gap. The model uses a probability diffusion concept to calculate the probability distribution of the leader in the gap. The solution of the diffusion problem is simplified by a problem-adapted coordinate transformation using a coordinate system based on the Laplacian background field. The diffusivity required is derived from a simplified physical model of the leader propagation mechanism. The model results are compared with experimental data from compressed SF_6 gaps and show satisfactory agreement.

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195. (*)

AUTHORS Niemeyer, L.; Pietronero, L.; Wiesmann, H. J.
TITLE Fractal Dimension of Dielectric Breakdown
TYPE journal
PAGE 1033-1036
JOURNAL Physical Review Letters
VOLUME 51
NUMBER 12
DATE March 19, 1984
KEYWORD model; fractal dimension; electrical breakdown

LANGUAGE	English
ABSTRACT	It is shown that the simplest nontrivial stochastic model for dielectric breakdown naturally leads to fractal structures for the discharge pattern. Planar discharges are studied in detail and the results are compared with properly designed experiments.

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196. (***)

AUTHORS	Nikezic, D. R.; Markovic, P. D.
TITLE	A Monte Carlo Calculation of the Exposure Dose Due to the Radioactive Lightning Rod
TYPE	journal
PAGE	91-93
JOURNAL	Acta Physica Hungarica
VOLUME	59
NUMBER	1
DATE	1985
KEYWORD	model; radiation protection; radioactive rod
LANGUAGE	English
ABSTRACT	A program is described which can be used to calculate the exposure dose rate due to the gamma sources used in radioactive lightning rods. Results obtained by using the developed program were compared with the experimentally obtained data. Relatively good agreement was found.

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197. (**)

AUTHORS	Norinder, H.; Siksna, R.
TITLE	Ionic Density of the Atmospheric Air Near the Ground During Thunder-Storm Conditions
TYPE	journal
PAGE	453-472
JOURNAL	Arkiv for Geofysik
VOLUME	1
NUMBER	16
DATE	Dec. 6, 1950
KEYWORD	measurement; ion density; thunder-storm; electric field; radioactive substances
LANGUAGE	English
ABSTRACT	COMMENT: This article reports on observations of a surface ionization phenomenon associated with thunderstorms. Measurements were performed at ground level with a simple arrangement. It is argued that corona discharge of the highly charged precipitation particles and the radioactive substances in precipitation may be the producers of the observed ions. The observed higher density of negative-ions compared to that of positive ions is attributed to the "Lenard effect". The effect of air transport of ions from higher altitudes does not appear to be of significance.

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198. (***)

AUTHORS Ortega. P.; Domens, P; Gilbert, A.; Hutzler, B.; Riquel, G.

TITLE Performance of a 16.7 m Air Rod-plane Gap under a Negative Switching Impulse

TYPE journal

PAGE 2379-2387

JOURNAL Journal of Physics D: Applied Physics

VOLUME 27

DATE 1994

KEYWORD experimental; air breakdown; switching impulse; lightning simulation; leader propagation

LANGUAGE English

ABSTRACT Experimental results of the development of a negative discharge in a 16.7 m rod-plane air gap are presented. Similarities with the cloud-to-earth discharge are found and some characteristic parameters are compared. Use of an image converter linked to two still cameras allows quite accurate analysis of the discharge propagation. Information relative to the space leader inception is provided. The current pulse shapes are related to the mechanisms of propagation and the thermal channel diameter of the discharge in the vicinity of the rod, which is measured with the help of schlieren records.

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199. (***)

AUTHORS Orville, R. E.

TITLE Cloud-to-ground Lightning Flash Characteristics in the Contiguous United States: 1989-1991

TYPE journal

PAGE 10833-10841

JOURNAL Journal of Geophysical Research

VOLUME 99

NUMBER D5

DATE May 20, 1994

KEYWORD survey; lightning occurrence; positive flashes; negative flashes

LANGUAGE English

ABSTRACT Wideband magnetic direction finders have been used to obtain a cloud-to-ground lightning flash count for the contiguous United States, an area of 7.7×10^6 km^2, for the period 1989 through 1991. Over 46 million flashes to ground were recorded and are divided among the three years, 13.4 million in 1989, 15.9 million in 1990, and 16.9 million in 1991. Maximum flash densities occur in Florida and increase each year, from 9 flashes/km^2 (1989) to 13 flashes/km^2 (1991). The database contains 1.7 million positive flashes divided among three years, 0.4 million in 1989, 0.6 million in 1990, and 0.7 million in 1991. In 1990 and 1991 the positive flash density maximum occurred in Florida, but elsewhere in 1989. Secondary maximum positive flash densities occur throughout the Midwest. The annual mean percentage of positive flashes in the total lightning count is 3.7% for the period 1989-1991. The interannual variation is small, ranging from 3.1%(1989) to 4.0%(1991). However, in any given year the geographical variation of the percentage of positive flashes is large. The percentage of positive flashes is 2%(1989) at the latitude of Florida but near 25% and higher at the latitudes of the upper Midwest, Maine, and Oregon.

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200. (**)

AUTHORS Orville, R. E.
TITLE Photographs of a Close Lightning Flash
TYPE journal
PAGE 666-667
JOURNAL Science
VOLUME 162
DATE Nov. 8, 1968
KEYWORD observation; lightning; photography
LANGUAGE English
ABSTRACT A lightning flash has been photographed striking a European ash tree at a distance of 60 meters. The tree sustained no external physical damage. The probability of obtaining this photograph is estimated to be 10^{-3}, or once in 1000 years.

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201. (**)

AUTHORS Orville, R. E.; Berger, K.
TITLE An Unusual Lightning Flash Initiated by an Upward-Propagating Leader
TYPE journal
PAGE 4520-4525
JOURNAL Journal of Geophysical Research
VOLUME 78
NUMBER 21
DATE July 20, 1973
KEYWORD observation; lightning; stepped leader; horizontal propagation
LANGUAGE English
ABSTRACT A lightning flash has been recorded that was initiated by an upward-propagating negatively charged stepped leader that followed a looping path and passed within 600 meters of the initiating tower. It continued for a horizontal distance of approximately 2 km before leaving the field of view of the camera. Current flowed for at least 100 msec with a peak current that did not exceed 1600 amp. The total charge transferred was approximately +30 to 40 coulombs.

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202. (**)

AUTHORS Orville, R. E.; Idone, V. P.
TITLE Lightning Leader Characteristics in the Thunderstorm Research International Program (TRIP)
TYPE journal
PAGE 11177-11192
JOURNAL Journal of Geophysical Research
VOLUME 87
NUMBER C13
DATE Dec. 20, 1982
KEYWORD observations; photography; lightning; leader
LANGUAGE English

ABSTRACT

We have used high speed streaking photographic techniques to time-resolve the luminous components of cloud-to-ground lightning flashes. All recordings were made during our participation in the Thunderstorm Research International Program (TRIP), conducted at the Kennedy Space Center, Florida, during the summers of 1977 and 1978, and at the Langmuir Laboratory near Socorro, New Mexico, during the summer of 1979. Twenty-one dart leaders, four dart-stepped leaders and three stepped leaders were recorded, the majority under daylight conditions. The mean two-dimensional propagation speed of the dart leaders, evaluated over channel lengths less than or equal to 0.8 km above ground is 11×10^6 m/s, with a range of 2.9×10^6 m/s. Several of the dart leaders reveal a decrease in propagation speed as ground is approached. However, four of the dart leaders in two separate flashes show increase in speed near the ground, an observation not previously reported in the literature. In two multistroke flashes, we examine the variation of dart leader propagation speed along the channel and find very similar behavior for different strokes in the same flash. The speed variations that we observe may be predominantly caused by geometrical variations of the channel. The dart leader propagation speeds reported in this study are compared with earlier works of Schonland, McEachron, and Kitagawa and Brook. Agreement among the studies is good, with a common range of observed dart leader propagation of 2 to 23×10^6 m/s. The major discrepancy among these studies is the observation, by Schonland, of a distribution of dart leader propagation speeds positively skewed toward the lower limit of reported values. Eleven of the dart leaders are analyzed at upper and lower levels along the visible channel to give 22 dart 'lengths.' They range from 7 to 75 m with a mean of 34 m. For these 22 determinations, we calculate correlation coefficient of 0.85 between the dart length and the dart leader propagation speed. The correlation of greater dart length with higher propagation speed is consistent with the slower decay of channel luminosity due to the greater initial input of energy to the channel by the faster and, presumably, more energetic dart leader. Four dart-stepped leaders are examined in detail with regard to variation of propagation speed, step length, stepping interval, and luminous intensity during propagation between the cloud base and ground. Significant differences in the tendencies of these parameters are found within these four leaders. For example, one dart-stepped leader recording shows a decreasing propagation speed and an increasing step interval near ground, whereas another shows the opposite behavior. In the best event recorded, several of the individual steps reveal a photographic film density structure, with the lower portion of the step exhibiting a distinct, bright tip that fans out into a symmetrically diffuse image in the upper portion of the step. Our analysis indicates that this spread in the upper portion of the step image is not the result of streaking photography distortion but, rather, represents the luminous structure of the step. We estimate that the step image is recorded in less than 1 microsecond. Consequently, with a measured step length of approximately 20 m, the luminous pulse must propagate along the step at a speed of at least 2×10^7 m/s. The mean propagation speed for three stepped leaders is found to be 1.1×10^6 m/s. All three stepped leaders are very faint, and were recorded only in the last 100-200 m above ground. Two stepped leaders and one dart-stepped leader do not propagate completely to ground before initiation of the return stroke. Apparently, these leaders are met by an upward propagating discharge at heights above the ground 20, 30, and 40 m, respectively. Other stepped and dart-stepped leader cases are indeterminate because an obstacle or horizon prevent recording of the leaders near the ground. Connecting discharges are not observed for any of the dart leader events with a resolution of 10 m at 5 km, implying that upward discharges initiated by the approach of the dart leader do not occur or are substantially less than a few tens of meters in length. Dart leaders, apparently, propagate completely to ground.

203. (**)

AUTHORS Parekh, H.; Srivastava, K. D.

TITLE Effect of Avalanche Space Charge Field on the Calculation of Corona Onset Voltage

TYPE journal

PAGE 181-191

JOURNAL IEEE Transactions on Electrical Insulation

VOLUME EI-14

NUMBER 4

DATE 1979

KEYWORD model; corona; electron avalanche; streamer; inception

LANGUAGE English

ABSTRACT Many researchers have suggested that the space charge field of the primary electron avalanche should not be neglected in calculating the corona onset voltage based on the streamer criterion. Some researchers consider only the space charge field of the positive ions created during the avalanche growth, while others consider only the space charge field of the electrons at the head of the avalanche. The authors suggest that both space charge fields should be considered in calculating the corona onset voltage. Computer programs are written to calculate the breakdown voltage (for uniform field: parallel-plane geometry) and corona onset voltage (for nonuniform field: point-to-plane geometry). The space charge fields of both the positive ions and electrons are considered in the calculations. Results are obtained for air and SF_6 for a wide range of geometrical parameters and gas pressures. The results indicate that the effect of space charge fields is to reduce the corona onset voltage (or breakdown voltage in uniform field geometry) by less than 5%.

COMMENT: A criticism of this work is that it does not adequately treat the effect of negative ions that may be important in electronegative gases like air and SF_6.

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204. (*)

AUTHORS Paxton, A. H.; Baker, L.; Gardner, R. L.

TITLE Natural Lightning Study 1985

TYPE report

SPONSOR Air Force Weapons Lab., Kirtland AFB

DATE Dec. 1, 1986

NTIS AD-A180 099/4/XAB

KEYWORD experimental; field; model

LANGUAGE English

ABSTRACT The principal results of MRC's lightning research during 1985, including the collaborations with the Langmuir Laboratory of the New Mexico Institute of Mining and Technology and the Air Force Weapons Laboratory, Kirtland Air Force Base, are described. Lightning strikes at the Kiva Facility of the Langmuir Laboratory have been observed and analyzed. The optical emissions and radiated electromagnetic field have been compared with computer simulations. The agreement is generally good. This facility is unique in the world, providing simultaneous measurements of stroke current, brightness, and radiated fields. The major discovery has been that the initial return stroke velocity is approximately 0.9 c as opposed to average stroke velocities reported to be about 0.3 c.

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205. (**)

AUTHORS Pedersen, A.
TITLE Calculation of Spark Breakdown or Corona Starting Voltages in Nonuniform Fields
TYPE journal
PAGE 200-206
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS-86
NUMBER 2
DATE Feb. 1967
KEYWORD theory; air breakdown; corona; streamer
LANGUAGE English
ABSTRACT The process leading to a spark breakdown or corona discharge are discussed briefly. A quantitative breakdown criterion for use in high-voltage design is derived by which spark breakdown or corona starting voltages in uniform fields can be calculated. The criterion is applied to the sphere gap, and it is shown how it can give a very detailed and accurate description of known breakdown characteristics.

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206. ( )

AUTHORS Petterson, B. J.; Wood, W. R.
TITLE Measurements of Lightning Strikes to Aircraft
TYPE report
SPONSOR Sandia Lab, Alberquerque, NM
DATE Jan. 1, 1968
NTIS AD-669 124
KEYWORD basic; experimental; field
LANGUAGE English
ABSTRACT Sandia's primary interest in a joint thunderstorm research effort was in the effect of lightning on nuclear weapons and on aircraft and missile wiring. A description of the test instrumentation, its installation in the aircraft, and an analysis of the results obtained is given. Flights were made into thunderstorms off the coast of Florida. Strikes were photographed and recorded, and the information was later analyzed. Although certain trends in effects were noted, no specific conclusions were drawn because of the limited nature of the experiment.

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207. (***)

AUTHORS Phelps, C. T.
TITLE Field-Enhanced Propogation of Corona Streamers
TYPE journal
PAGE 5799-5806
JOURNAL Journal of Geophysical Research
VOLUME 76
NUMBER 24
DATE Aug. 20, 1971

KEYWORD streamers; corona; experiment; humidity; water drop
LANGUAGE English
ABSTRACT Experiments are described in which the lengths of positive and negative streamers, propagating within a region characterized by a uniform electric field, are determined as a function of field strength. Streamers were generated from the application of a short rise-time voltage pulse to a point electrode and from field-induced hydrodynamic instability of a falling water drop. Positive streamers display marked length enhancement with ambient electric fields in the direction of propagation greater than about 6×10^5 V/m and lengths apparently limited only be the spatial extent of the field above about 7×10^5 V/m, depending somewhat upon the absolute humidity of the air. Negative streamers show only a small length enhancement with ambient fields as high as 8×10^5 V/m. The results with positive streamers are discussed in terms of a model in which the propagating tip becomes isolated from its anode source and derives energy from interaction with the ambient electric field. Since the ambient field within an active thundercloud may reasonably attain the necessary strength for long-range propagation, these results suggest that positive streamer processes may be very important in charge drainage and altering the droplet charge spectrum.

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208. (**)
AUTHORS Phelps, C. T.
TITLE Positive Streamer System Intensification and Its Possible Role in Lightning Initiation
TYPE journal
PAGE 103-111
JOURNAL Journal of Atmospheric and Terrestrial Physics
VOLUME 36
DATE 1974
KEYWORD streamers; lightning initiation; experiment; stepped leader
LANGUAGE English
ABSTRACT Experiments are described in which positive streamers propagate within a uniform field region having an applied electric field greater than the minimum value needed to cause streamers to bridge the interelectrode gap. Under these conditions exponential intensification of the streamer system is observed, accompanied by negative charge deposition along the channels. These results are shown to be a direct consequence of energy and charge conservation for the streamer system when individual streamers are treated as isolated propagating space charge pulses. The formation of a stepped leader via this process is discussed.

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209. (*)
AUTHORS Phillpott, J.; James, T. E.
TITLE Simulation of Lightning Strikes to Aircraft
TYPE report
SPONSOR UKAEA, Abingdon, Berks. UK
DATE May 1, 1971
KEYWORD aircraft; experimental; simulation
LANGUAGE English

ABSTRACT This report reviews the aspects of natural lightning and identifies the major parameters relevant to aircraft damage. The simulation of this damage in the laboratory, the general studies deemed necessary, and the design of the high current simulation facilities are considered, together with comments on the existing test waveforms and a proposed future test specification. The problem of predicting strike point locations and the validity of model tests using a high voltage generator are discussed, together with comments on methods of determining the value of probability of a strike to a given region.

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210. (**)

AUTHORS Piepgrass, M. V.; Krider, E. P.; Moore, C. B.
TITLE Lightning and Surface Rainfall During Florida Thunderstorms
TYPE journal
PAGE 11193-11201
JOURNAL Journal of Geophysical Research
VOLUME 87
NUMBER C13
DATE Dec. 20, 1982
KEYWORD observations; lightning statistics; electric field; rainfall
LANGUAGE English
ABSTRACT Electric field records have been computer analyzed to determine the lightning statistics for air-mass thunderstorms at the NASA Kennedy Space Center, Florida. The results for 79 summer storms which produced 10 or more discharges during the years 1976-1980 indicate that cloud-to-ground discharges occur at a mean rate of about 2.4 discharges per minute per storm. The maximum flashing rate over a 5-min interval was 30.6 discharges per minute on July 14, 1980. Estimates of the monthly area density of all discharges during June, July, and August 1974 through 1980 range from 4 to 27 discharges per km^2 per month, with a systematic uncertainty of perhaps a factor of 2 in the sampled area. The mean and standard deviation of the monthly area density over the above years was 12 ± 8 discharges per km^2 per month, and the mean area density of just cloud-to-ground (CG) flashes is estimated to be 4.6 ± 3.1 CG flashes per km^2 per month. Tipping-bucket rain gauges were operated at each field mill site during 1976, 1977, and 1978 as part of the Thunderstorm Research International Program, and the statistics on rainfall are given for 28 storms in 1977 and 1978. Two thunderstorms, one small and one large, were favorably located and relatively stationary, so that the lightning data and surface rainfall could be directly compared. In these storms, there was a good correlation between lightning and rainfall when the latter lagged the former by times of 4 and 9 min. The average rainfall associated with each lightning is estimated to be about 6.7×10^3 m^3 per discharge during the small storm and about 8.5×10^3 m^3 per discharge during the large storm. The average rain volumes associated with each cloud-to-ground flash are estimated to be 1.8×10^4 m^3 per CG flash and 2.2×10^4 per CG flash during these storms, values that are in good agreement with estimates by other investigators.

COMMENT: The results of this investigation have significant implications for testing of lightning protection systems in two respects. First, it is seen that, even in areas like Florida where the frequency of thunderstorm occurrence is high, the probability per unit time of lightning strikes at any one location is relatively low; thus pointing to the difficulty of obtaining statistically significant data in a reasonable time required for meaningful field tests in the natural environment.

Secondly it shows a significant correlation between rainfall rate and the likelihood of a cloud-to-ground lightning strike at any given location which may need to be considered in designing realistic tests of lightning protection devices.

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211. (*)

AUTHORS Pierce, E. T.
TITLE Natural Lightning Parameters and their Simulation in Laboratory Tests
TYPE conference
PAGE 13
CONFERENCE 1975 Conference on Lightning and Static Electricity
LOCATION Abingdon, Berks. UK
DATE April 14, 1975
KEYWORD aircraft; review; simulation; simulation evaluation
LANGUAGE English
ABSTRACT Summarizes present knowledge of lightning. Firstly, it attempts to enable those concerned with operations involving aircraft and rockets to assess correctly the hazards associated with lightning. Secondly, it tries to define realistic criteria for laboratory simulation tests aimed at assisting designers in reducing lightning vulnerability.

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212. (***)

AUTHORS Preece, W. H.
TITLE On the Space Protected by a Lightning-Conductor
TYPE journal
PAGE 427-430
JOURNAL Philosophical Magazine and Journal of Science
VOLUME 10
NUMBER 5
DATE July-Dec. 1880
KEYWORD model; lightning; zone of protection
LANGUAGE English
ABSTRACT COMMENT: This paper appears to be the original source for the conic zone-of-protection concept as applied to vertical lightning conductors (Franklin rods). The paper contains the following statements: "Hence a lightning-rod protects a conic space whose height is the length of the rod, whose base is a circle having its radius equal to the height of the rod, and whose side is the quadrant equal to the height of the rod, and whose radius is equal to the height of the rod. I have carefully examined every record of accident that I could examine, and I have not yet found one case where damage was inflicted inside this cone when the building was properly protected."

It should be noted that the zone-of-protection concept proposed in this work is based on an idealistic, simplistic symmetrical electrostatic model of the perturbation of a uniform electric field under a cloud that occurs around a conductive protrusion on a flat plane. It does not consider the statistical variability of lightning strokes and such factors as space charge that modify the electric field beneath a thundercloud and are now known to significantly influence the path of lightning. The source of "records of accident" mentioned in the paper are not identified.

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213. (**)

AUTHORS Reather, H.
TITLE The Development of an Electron Avalanche into a Spark Channel
TYPE journal
PAGE 464-489
JOURNAL Zietschrift fur Physik
VOLUME 112
DATE 1939
KEYWORD experiment; electron avalanche; streamer development
LANGUAGE German
ABSTRACT COMMENT: This work is of historical interest because it reports one of the first observations of the development of an electron avalanche into a fast spark channel (streamer), and because it postulates the streamer propagation mechanism. In this work, the high streamer-propagation velocities in the range of 1 to $2x10^8$ cm/s were first observed.

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214. (**)

AUTHORS Reininghaus, W.
TITLE Calculation of Streamers in Gaseous Discharges
TYPE journal
PAGE 1486-1493
JOURNAL Journal of Physics D: Applied Physics
VOLUME 6
DATE 1973
KEYWORD streamer; model; light emission
LANGUAGE English
ABSTRACT A computer program is described which imitates the slow phase of the cathode-directed streamer in gaseous discharges. The results of our calculations show the development of space-charge fields which cause the cathode-directed streamer. The involved densities of electrons and ions are calculated. The mechanism and the development of the cathode-directed streamer are described in detail. By comparing the calculated emitted light intensity with experimental short-time photographs of the streamer we determined the amount of secondary electrons necessary to initiate and sustain the streamer.

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215. (**)

AUTHORS Rison, W.
TITLE A Study of Lightning Strikes in the Vicinity of a Radioactive Terminal
TYPE report
PUBLISHER Rison, W. New Mexico Tech, Langmuir Laboratory, Socorro, New Mexico 87801
DATE 1991
KEYWORD observations; radioactive terminal; lightning strikes
LANGUAGE English

ABSTRACT

On two known occasions during a six-week period, lightning struck within the claimed zone of protection of a radioactive terminal. This shows that the terminal does not protect a region of 100 meter radius from lightning strikes. It does not prevent lightning from striking within the specified zone of protection, nor does it collect the lightning which it fails to prevent. There is no evidence, either from this study or from the previous study that the radioactivity in the terminal enhances its effectiveness as a lightning terminal. All the evidence from both studies is that an inexpensive Franklin-type rod is as effective a lightning terminal as is a radioactive terminal.

COMMENT: This is an unreviewed report prepared at a university.

NOTE: The original title and abstract of this report contained references to specific commercial devices by trade name which have been deleted.

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216. (**)

AUTHORS Rison, W.

TITLE A Comparison of the Corona Current from a Radioactive and Non-Radioactive Terminal

TYPE report

PUBLISHER Rison, W. New Mexico Tech, Langmuir Laboratory, Socorro, New Mexico 87801

DATE 1991

KEYWORD observations; radioactive terminal; corona; lightning

LANGUAGE English

ABSTRACT

The test described in this report shows that, under strong fields of a thunderstorm, a radioactive and a non-radioactive terminal had essentially the same point-discharge current. Radioactivity did not enhance the ionization capability of the terminal under these circumstances. Similar results were found by other scientific studies of radioactive vs. non-radioactive terminals (as reviewed by Golde). In my opinion, the radioactive terminal is no more effective as a lightning terminal than a non-radioactive terminal or a standard Franklin rod.

The only 100% effective lightning protection system is a complete Faraday cage, in which the object to be protected is completely surrounded by a metal shield. Since this is impractical for large structures, an alternative must be used. Protection effectiveness approaching 100% can be accomplished using standard lightning protection procedures of a modified Faraday cage and air terminals. A single terminal protecting an area of 450,000 sq ft. is ineffective. It can also be dangerous if the customer believes he is protected when he really is not. For example, someone assuming he was protected could be struck by lightning while working in such an area, or an explosion or fire could be initiated if explosive or flammable material were stored in such an unprotected area.

COMMENT: This is an unreviewed report prepared at a university.

NOTE: The original title and abstract of this report contained references to specific commercial devices by trade name which have been deleted.

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217. (**)

AUTHORS Rizk, F. A. M.

TITLE Critical Switching Impulse Strength of Long Air Gaps: Modelling of Air Density Effects

TYPE journal

PAGE 1507-1515

JOURNAL IEEE Transactions on Power Delivery

VOLUME 7

NUMBER 3

DATE July, 1992

KEYWORD switching impulse; breakdown; air density; model

LANGUAGE English

ABSTRACT The paper presents a physical modelling approach to investigate the effect of reduced air density on leader inception and sparkover of long air gaps under positive switching impulses with critical front time. The model accounts for the effect of air density on continuous leader inception voltage, leader length and sparkover voltage. The results of the model provide critical positive switching impulse air density correction factors for rod-plane, rod-rod, conductor-plane, conductor-rod and conductor-tower window gaps over a wide range of gap distances and relative air densities. The model findings were extensively checked against previous experimental results with quite satisfactory agreement.

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218. (**)

AUTHORS Rizk, F. A. M.

TITLE Modeling of Lightning Incident to Tall Structures, Part II. Application

TYPE conference

PAGE 93 WM 081-0

CONFERENCE IEEE Winter Power Engineering Society Meeting

LOCATION Columbus, Ohio

SPONSOR IEEE

DATE Jan. 31, 1993

KEYWORD model; lightning; leader; mast; shielding

LANGUAGE English

ABSTRACT The present paper comprises an extensive computer investigation of lightning incidence to tall masts, based on a theory presented in a companion paper, for both flat and hilly regions. The investigation covers both downward negative lightning incidence and upward flash from tall masts under negative cloud. The factors investigated include: mast height, statistical distribution of the ground electric field, as well as mountain height and topology. Predicted lightning incidence and probability of upward flash are successfully verified against extensive field observations.

COMMENT: Particular attention should be paid to this paper because it describes a method for computing striking distances that may prove useful in defining zones of protection that take into account the statistical variability of a lightning strike.

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219. (**)

AUTHORS	Rizk, F. A. M.
TITLE	A Model for Switching Impulse Leader Inception and Breakdown of Long Air-Gaps
TYPE	journal
PAGE	596-606
JOURNAL	IEEE Transactions on Power Delivery
VOLUME	4
NUMBER	1
DATE	Jan. 1989
KEYWORD	streamer; leader; switching impulse; breakdown; air insulation; model
LANGUAGE	English
ABSTRACT	The paper introduces a new mathematical model for continuous leader inception and breakdown of long air gaps under positive switching impulses with critical time-to-crest. The model deals with rod-, sphere- and conductor- plane gaps. It provides novel analytical expressions for continuous leader inception voltage, height of the final jump and breakdown voltage as well as analytical tools to determine the critical electrode radius for any gap spacings. The theory is extensively compared with previous experimental results and is tested against several formerly developed empirical formulae, relevant to several discharge parameters, for different electrode forms and over a wide range of gap spacings.

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220. (**)

AUTHORS	Rizk, F. A. M.
TITLE	Modeling of Lightning Incidence to Tall Structures, Part I: Theory
TYPE	conference
PAGE	93 WM 082-8
CONFERENCE	IEEE Winter Power Engineering Society Meeting
LOCATION	Columbus, Ohio
SPONSOR	IEEE
DATE	Jan. 31, 1993
KEYWORD	model; lightning; leader; mast; shielding
LANGUAGE	English
ABSTRACT	The paper generalizes a recent physical approach to assess negative downward lightning incidence to apply to tall masts and hilly regions. Criteria for occurrence of an upward flash from a tall structure under negative cloud are formulated both for flat and hilly terrain. Finally the effect of structure on statistical stroke current distribution is analytically investigated. Extensive computer investigation to apply the theory as well as comparison with field observations are reported in a companion paper.

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221. (***)

AUTHORS	Rizk, F. A. M.
TITLE	Modeling of Transmission Line Exposure to Direct Lightning Strokes
TYPE	journal
PAGE	1983-1997

JOURNAL IEEE Transactions on Power Delivery
VOLUME 5
NUMBER 4
DATE Nov. 1990
KEYWORD model; lightning; positive leader; attractive distance; transmission line; shielding
LANGUAGE English
ABSTRACT The paper introduces a new model for assessing the exposure of free-standing structures and horizontal conductors above flat ground to direct lightning strokes. The starting point of this work is a recently developed criterion for positive leader inception, modified to account for positive leaders initiated under the influence of a negative descending lightning stroke. Subsequent propagation of the positive leader is analyzed to define the point of encounter of the two leaders which determines the attractive radius of a structure or the attractive lateral distance of a conductor. These parameters are investigated for a wide range of heights and return stroke currents. A method for analyzing shielding failure and determining the critical shielding angle is also described. The predictions of the model are compared with field observations and previously developed models.

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222. (*)
AUTHORS Rizk, F. A. M.
TITLE Critical Switching Impulse Breakdown of Long Bundle-Conductor Gaps
TYPE conference
PAGE 1-9
CONFERENCE IEEE Winter Power Engineering Society Meeting
LOCATION New York, New York
SPONSOR IEEE
DATE Jan. 29, 1995
KEYWORD model; air breakdown; switching impulse; bundle conductors
LANGUAGE English
ABSTRACT The paper presents a generalized physical approach to account for the effect of bundle geometry on critical switching impulse strength of long air gaps. The model covers phase-to-ground as well as phase-to-phase insulation. It has been applied to conventional symmetrical bundles as well as to more complex open configurations. The effect of bundle conductors was investigated for the following basic configurations: conductor-plane, conductor-rod, conductor-tower window as well as phase-to-phase, within a wide range of clearances. The model is compared with previous analytical approaches as well as extensive experimental results.

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223. (**)
AUTHORS Rizk, F. A. M.
TITLE Switching Impulse Strength of Air Insulation: Leader Inception Criterion
TYPE journal
PAGE 2187-2195
JOURNAL IEEE Transactions on Power Delivery
VOLUME 4

NUMBER 4
DATE Oct. 1989
KEYWORD leader; switching impulse; breakdown; long air gaps; theory
LANGUAGE English
ABSTRACT The paper introduces a general criterion for leader inception of phase-to-ground air insulation under positive critical switching impulses. The new leader inception criterion establishes the correspondence between continuous leader initiation in the vicinity of the highly stressed electrode and conditions prevailing later at the instant of the final jump. The criterion is then applied to several complex electrode configurations including rod-rod, conductor-rod and conductor-structure gaps, where both analytic and digital techniques are used to compute the leader inception voltage, 50% breakdown voltage and gap factor. The theoretical predictions are systematically compared with available experimental results.

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224. ( )
AUTHORS Robb, J. D.; Plumer, J. A.
TITLE Aerospace Recommended Practice: Lightning Effects Tests on Aerospace Vehicles and Hardware
TYPE conference
PAGE 12
CONFERENCE 1975 Conference on Lightning and Static Electricity
LOCATION Abingdon, Berks. UK
DATE April 14, 1975
KEYWORD review; simulation; simulation evaluation
LANGUAGE English
ABSTRACT Summarises a draft of a Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) prepared since the 1972 Lightning and Static Electricity Conference in an attempt to standardise lightning test waveforms and techniques in the United States. The ARP was prepared as the result of a long-standing and often expressed need within the United States aerospace community for a definitive, comprehensive guide to lightning simulation and verification testing of aerospace vehicles. The document was prepared with the realization and intent that major portions of it may be adopted as the basis for specifications and standards. The ARP defines a standardised set of test waveforms based on the best available knowledge of the natural lightning environment, coupled with a practical consideration of state-of-the-art laboratory techniques, remembering that the purpose of simulation testing is to produce the significant effects on the environment and not the details of the environment itself.

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225. (***)
AUTHORS Roberts, J. E.
TITLE Ionizing Radiation and Lightning Hazards
TYPE journal
PAGE 514-515
JOURNAL Nature
VOLUME 210

DATE April 30, 1966
KEYWORD ionizing radiation; lightning conductor; lightning protection; critique
LANGUAGE English
ABSTRACT COMMENT: Additional arguments are presented in support of the opinion previously expressed by P. J. Gillespie [Nature, Vol. 208, pp. 577 (1965)] that small radioactive sources attached to a lightning conductor are ineffective in attracting lightning and that users of large sources of ionizing radiations in hospitals and industry do not have an elevated risk of lightning strikes. Estimates are made which indicate that the rate of ion pair formation in the atmosphere due to small radioactive sources is significantly below the rate from natural background radiation within the proposed sphere of protection.

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226. (**)
AUTHORS Ryzko, H.
TITLE The Transition from Multiple-Avalanche to Single-Avalanche Mechanism in the Breakdown of Air in a Homogeneous Field
TYPE journal
PAGE 481-507
JOURNAL Arkiv for Fysik
VOLUME 25
NUMBER 35
DATE 1963
KEYWORD experiment; electron avalanche; air breakdown; water vapor effect; statistical time lags
LANGUAGE English
ABSTRACT The transition region from the multiple- to the single-avalanche mechanism of breakdown has already been investigated in irradiated gaps [1,2]. This transition region can be indicated more precisely in non-irradiated gaps but here the ordinary technique for formative time lag measurement cannot be applied. The new experimental technique has therefore been worked out. The formative time is measured by one oscilloscope whose time-base is triggered by the photo-pulse of the primary avalanche itself, this pulse being taken via photo-multiplier. For the determination of the potential maintained across the gap during spark formation, the statistical time lag must be known. This time lag measured by a second oscilloscope with the time-base, which is triggered by a steep potential of variable amplitude abruptly applied to the gap by means of hydrogen thyratron. As at pd = 600 cm × mm Hg the transition from the multiple- to the single-avalanche mechanism of breakdown was before investigated only for dry air [1], we performed the measurement for this value of pd in humid air. When p_w = 15 mm Hg, the change of mechanism in breakdown took place at overvoltages of 4% to 6%. This value is much lower than for dry air (8%) given in [1].

[1] Kohrman, W., Z. ang. Phys., Vol. 7, 187 (1955); Applied Scien. Research BV, 288 (1956).

[2] Raether, H., Ergeb. exakten Naturwiss. Vol. 33, 175 (1961).

COMMENT: This work demonstrates the significant effect of water vapor on electrical breakdown in air.

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227. (**)

AUTHORS Salama, M. M. A.; Parekh, H.; Srivastava, K. D.
TITLE Model for Switching Surge Breakdown of a Point-to-Plane Air Gap
TYPE journal
PAGE 4426-4429
JOURNAL Journal of Applied Physics
VOLUME 47
NUMBER 10
DATE October 1976
KEYWORD streamer; model; experiment; air breakdown; corona
LANGUAGE English
ABSTRACT A theoretical model for streamer propagation and subsequent breakdown in a long air gap is proposed. A rod-to-plane geometry is considered and a switching voltage of positive polarity is applied to the rod electrode. Results are obtained for different rod radii and gap lengths. The computed results are compared with the experimental results.

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228. (**)

AUTHORS Salama, M. M. A.; Parekh, H.; Srivastava, K. D.
TITLE Corona Inception under Switching Surge for Point-to-Plane Long Gaps
TYPE journal
PAGE 2915-2917
JOURNAL Journal of Applied Physics
VOLUME 47
NUMBER 7
DATE July 1976
KEYWORD model; corona; switching impulse; inception voltage
LANGUAGE English
ABSTRACT This paper describes a method of calculating the corona-inception voltage and its probability for a point-to-plane long gap and under a switching surge of positive polarity. The minimum corona-inception voltage is determined by calculating the number of electrons at the head of a primary avalanche. The statistical probability of corona inception is determined by calculating the critical volumes (areas) in space at different voltages above the minimum corona-inception voltage. The derivative of the critical volume (or area) with respect to time gives a measure of the statistical probability of corona-inception voltage.

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229. (**)

AUTHORS Salama, M. M. A.; Parekh, H.; Srivastava, K. D.
TITLE A Comment on the Methods of Calculation of Corona Onset Voltage
TYPE journal
PAGE 139-141
JOURNAL Applied Physics Letters
VOLUME 30

NUMBER 3
DATE Feb. 1, 1977
KEYWORD model; corona; onset; electron avalanche; air gaps
LANGUAGE English
ABSTRACT Two methods of calculating corona onset voltage (COV) in nonuniform air gaps are studied. The variation of number of electrons (or positive ions) in primary and secondary electron avalanches for short (< 20 cm) as well as long (2-10 m) positive point-to-plane air gaps is obtained. Several conclusions regarding critical charge carrier numbers are drawn from this study.

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230. (***)
AUTHORS Sargent, M. A.
TITLE The Frequency Distribution of Current Magnitudes of Lightning Strokes to Tall Structures
TYPE journal
PAGE 2224-2229
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS-91
NUMBER 5
DATE Sept./Oct. 1972
KEYWORD survey; model; lightning strokes; statistical distributions; tall structures
LANGUAGE English
ABSTRACT The frequency distribution of stroke current magnitudes proposed in the literature are examined to evaluate the influences that height and type of structure have on the distribution of current magnitudes observed in the structures. These analyses have been performed using a three-dimensional electro-geometric model [1]. Results indicate that both the height and type of the structure on which current measurements are made significantly influence the observed frequency distribution. It is suggested that these effects contribute to the differences existing between alternative distributions found in the literature.

[1] M. A. Sargent, "Monte Carlo Simulation of the Lightning Performance of Overhead Shielding Networks of High Voltage Stations," Paper submitted for the IEEE Winter Power Meeting, 1972.

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231. (*)
AUTHORS Schnetzer, G. H.; Fisher, R. J.
TITLE Sandia Transportable Triggered Lightning Instrumentation Facility
TYPE report
SPONSOR National Aeronautics and Space Administration
DATE Aug. 1, 1991
NTIS N91-32636/3/XAB
KEYWORD experimental; rocket; simulation; triggered
LANGUAGE English

ABSTRACT Development of the Sandia Transportable Triggered Lightning Instrumentation Facility (SATTLIF) was motivated by a requirement for the in situ testing of a munitions storage bunker. Transfer functions relating the incident flash currents to voltages, currents, and electromagnetic field values throughout the structure will be obtained for use in refining and validating a lightning response computer model of the facility under actual operational conditions was performed during summer of 1990 at the Kennedy Space Center's (KSC) rocket-triggered lightning test site. A description is given of the SATTLIF, which is readily transportable on a single flatbed truck or by aircraft, and its instrumentation for measuring incident lightning channel currents and the responses of the systems under test. Measurements of return-stroke current peaks obtained with the SATTLIF are presented. Agreement with data acquired on the same flashes with existing KSC instrumentation is, on average, to within approximately 7 percent. Continuing currents were measured with a resolution of approximately 2.5 A. This field trial demonstrated the practicality of using a transportable triggered lightning facility for specialized test applications.

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232. (**)

AUTHORS Schonland, B. F. J.
TITLE Development of the Lightning Discharge
TYPE journal
PAGE 407-408
JOURNAL Nature
VOLUME 132
DATE Sept. 9, 1933
KEYWORD lightning; photographic observations; leader
LANGUAGE English
ABSTRACT COMMENTS: This work shows photographic records of lightning development which reveal that the combination of a downward-moving 'leader' with a stronger upward stroke to be very frequent.

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233. (**)

AUTHORS Schonland, B. F. J.; Maln, D. J.; Collens, H.
TITLE Progressive Lightning - II
TYPE journal
PAGE 595-625
JOURNAL Proceedings of the Royal Society of London, Series A
VOLUME 152
DATE 1935
KEYWORD lightning; observations; photography; statistical distributions
LANGUAGE English
ABSTRACT A general account based on the study of 95 flashes with the Boys and other cameras, is given of the mode of development of the lightning discharge. A statistical study is made of the distribution of the strokes of a discharge in respect of number, time-interval, intensity, and manner of branching. It is shown that the leader-return stroke sequence is present in almost all cases examined. Leaders to first strokes are stepped, those to subsequent strokes generally dart like. In certain cases of very slow dart leaders, these change to the stepped form at their lower ends. It is shown that slower leader velocities and higher intensities of return strokes are associated with longer time-intervals between strokes and their predecessors, and hence that the degree of pre-existing ionization in the

channel governs the velocity of the dart leader. The downward-branching of lightning and its characteristic zig-zag form are shown to arise during the stepped-leader process before the first return stroke. A decrease in the intensity of the return portion of a stroke in passing branch points is found to be general, and it is deduced that the leader process lowers into the air a very considerable fraction of the cloud charge tapped.

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234. ( )

AUTHORS Schufft, W.; Schrader, W.
TITLE New Marx Generator for the Simulation of Lightning Impulse Voltages and Currents
TYPE conference
PAGE 453-456
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; simulation; Marx generator
LANGUAGE English
ABSTRACT To guarantee the reliability of electronic control equipment in electric power systems such equipment must be proof against EMP - especially lightning strokes. Modern MARX-generators are suited for the simulation of both, impulse voltages and the very critical, steep current pulses. In the latter case they have to meet the requirements for a low self-inductivity and a variable circuitry.

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235. (*)

AUTHORS Schulte, E. H.
TITLE Updating the McAir Lightning Simulation Laboratory
TYPE report
SPONSOR McDonnell Aircraft Company, St. Louis, MO
NTIS AD-P002 222/8
DATE 1983
KEYWORD review; simulation; simulation evaluation
LANGUAGE English
ABSTRACT The goal of lightning simulation testing of aircraft is to ensure flight safety. The realism of each simulation is limited by the complexities of both the lightning environment and the aircraft itself. As the natural threat becomes better understood and improved test techniques are developed, the modern lightning laboratory must continually upgrade its equipment and facilities to meet the need for more accurate test simulation. This paper describes the major accurate test simulation improvements incorporated in the McDonnell Aircraft Company lightning laboratory.

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236. (*)

AUTHORS	Schulte, E. H.
TITLE	The McDonnel Aircraft Company Lightning Simulation Laboratory
TYPE	journal
PAGE	22-27
JOURNAL	Journal of Environmental Sciences
VOLUME	22
NUMBER	3
DATE	May 1979
KEYWORD	practical; simulation; simulation evaluation
LANGUAGE	English
ABSTRACT	Describes how techniques are applied in some of the unique generators used for conducting high-voltage, high-current, swept stroke, and induced-transient simulated lightning tests. The various equipment and facilities which are available at MCAIR for performing lightning simulation tests are tested and examples of some of the tests performed are discussed.

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237. (*)

AUTHORS	Schulte, E. H.
TITLE	Lightning Damage Mechanisms and Simulation Techniques
TYPE	journal
PAGE	13-17
JOURNAL	Journal of Environmental Sciences
VOLUME	23
NUMBER	3
DATE	May 1980
KEYWORD	aircraft; review; simulation
LANGUAGE	English
ABSTRACT	This paper describes the natural lightning phenomena to show how this relates to aircraft and the need for protection. It also illustrates how the various aspects of lightning can be simulated in the laboratory and the need for continued upgrading of test techniques.

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238. (**)

AUTHORS	Selim, E. O.; Waters, R. T.
TITLE	Space Charge Modelling in Impulse Corona
TYPE	conference
CONFERENCE	Fourth International Symposium on High Voltage Engineering
LOCATION	Athens, Greece
DATE	Sept. 5, 1983
KEYWORD	experiment; corona; air breakdown; space charge; electric-field measurement
LANGUAGE	English
ABSTRACT	Simultaneous field measurements together with charge flow have been made in a 450 mm sphere/plane gap subjected to positive and negative impulse voltages. Charge-simulation computations show that the data are inconsistent with unipolar space-charge models.

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239. (**)

AUTHORS Shindo, T.; Aihara, Y.
TITLE Shielding Theory for Upward Lightning
TYPE journal
PAGE 318-324
JOURNAL IEEE Transactions on Power Delivery
VOLUME 8
NUMBER 1
DATE Jan. 1993
KEYWORD shielding; theoretical; upward leader
LANGUAGE English
ABSTRACT A new shielding theory is proposed based on the assumption that the occurrence of lightning strokes on the Japan Sea coast in winter is due to the inception of upward leaders from tall structures. Ratios of the numbers of lightning strokes to high structures observed there in winter show reasonable agreement with values calculated by this theory. Shielding characteristics of a high structure in various conditions are predicted.

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240. (*)

AUTHORS Shindo, T.; Aihara, Y.; Miki, M.; Suzuki, T.
TITLE Model Experiments of Laser-Triggered Lightning
TYPE journal
PAGE 311-317
JOURNAL IEEE Transactions on Power Delivery
VOLUME 8
NUMBER 1
DATE Jan. 1993
KEYWORD experimental; guided; laser; theoretical
LANGUAGE English
ABSTRACT Experiments to guide electric discharges with a chain of apparently discrete air-breakdown plasmas (plasma channel) produced by a laser were carried out. The electric discharge was guided up to 2 m with a high power CO_2 laser focused by a 10 m focal length mirror. Voltage was applied at selected delay times τ following laser radiation. The relations between 50% flashover voltage of a gap filled with laser-produced plasmas and delay times τ, between the guided length and the peak of the applied voltage, were obtained experimentally. The effects of the polarity of an applied voltage and the position of the plasma channel on flashover voltage are described. Development characteristics of the guided discharge were also investigated.

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241. (**)

AUTHORS Shindo, T.; Aihara, Y.; Suzuki, T.
TITLE Model Experiment of Upward Leaders - Shielding Effects of Tall Objects
TYPE journal
PAGE 716-723
JOURNAL IEEE Transactions on Power Delivery
VOLUME 5
NUMBER 2
DATE April 1990

KEYWORD experimental; model; shielding; upward leader
LANGUAGE English
ABSTRACT Discharges originating from laboratory upward leaders are studied experimentally with a configuration consisting of two parallel vertical rods at ground and an elevated plane. The flashover probability of each rod, the effect of gap configuration on the probability, and the shielding effect of the taller rod on the smaller one are investigated. Experimental results are analyzed, taking into account the deviation of time to flashover of the gap. Application of the results to the case of natural lightning is also discussed.

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242. (*)
AUTHORS Shindo, T.; Miki, M.; Aihara, Y.; Wada, A.
TITLE A Study of Laser-Triggered Lightning--Calculation of Plasma Generation Along a Laser Beam
TYPE conference
PAGE 305-308
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; laser; plasma channel; theoretical
LANGUAGE English
ABSTRACT Air-breakdown plasma production along a high power laser beam is calculated with two basic formulae, i.e. laser beam propagation and cascade ionization. Calculated results are compared with experimental results. Effects of laser power and focusing systems on the plasma production are estimated.

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243. (*)
AUTHORS Shindo, T.; Sasaki, S.
TITLE Development of Laser Technology for Lightning Induction
TYPE journal
PAGE 739-746
JOURNAL Journal of the Institute of Electrical Engineers of Japan
VOLUME 111
NUMBER 9
DATE Sept. 1991
KEYWORD applications; guided; laser; plasma channel; practical; triggered
LANGUAGE Japanese
ABSTRACT When the beam of a large power laser is focused in the air, dielectric breakdown of the gas takes place along the length of the laser beam. An electric discharge is induced and developed along such a plasma area of dielectric breakdown between the gap where high tension is applied. Laser-applied lightning induction is a technology used to prevent lightning from hitting electric power facilities directly, by forming a linear dielectric breakdown area (plasma channel) from the ground to the thundercloud, using laser beams. Intensive studies have been made by many research organizations in order to develop laser-applied lightning induction which realizes perfect shielding against lightning. The authors describe the outline of dielectric breakdown of gases by the use of laser technology, and details the present and future trends of studies into laser-applied lightning induction.

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244. (**)

AUTHORS Shipley, J. F.

TITLE The Protection of Structures Against Lightning

TYPE journal

PAGE 501-523

JOURNAL The Journal of The Institution of Electrical Engineers Part I

VOLUME 90

DATE 1943

KEYWORD lightning protection; zone of protection; air terminals; down conductors

LANGUAGE English

ABSTRACT The British Standards Institution has just issued a set of Recommendations on this subject, which is the first authoritative general guidance that has been made available to the public in this country since the Report of the Lightning Rod Conference in 1881 and its amendment by the Lightning Research Committee in 1905. These new recommendations have been adopted and published by Codes of Practice Committee for Civil Engineering Works and Buildings formed under the aegis of the Ministry of Works and Planning. The Code of Practice should be referred to because in addition to the Recommendations it contains appendices in which comment is made on some of the new features dealt with, and which this paper to some extent amplifies. This paper does not deal with the protection of ships, aircraft or electric supply and telephone wires, but it attempts to throw light upon the problems connected with the protection of modern steel-framed and ferro-concrete structures. The need for protection is discussed and a rough attempt is made to assess the risk attached to any structure in any part of the world. The zone of protection receives attention and the presence of metal in the buildings is debated. The needs of structures which are very vulnerable to lightning, and of others which present difficult problems, are discussed. The components of a protective system, their materials and dimensions, together with their cost are referred to, and finally inspection, testing and records are dealt with.

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245. (***)

AUTHORS Soibelzon, H. L.

TITLE Do Lightning Arresters with a Radioactive Transmitter Provide a Wider Field of Protection than Franklin Lightning Arresters?

TYPE journal

PAGE 128-135

JOURNAL Revista Electrotecnica

VOLUME 64

NUMBER 4

DATE July-Aug. 1978

KEYWORD critique; radioactive rod

LANGUAGE Spanish

ABSTRACT Because it is difficult to solve this problem without adequate experimentation, the author gives a translation of a Swiss article on research which gives a negative answer to this question. After indicating that point lightning arresters are not as efficient as a mesh system, the article translated investigates the theory prompted by an English collaborator of Mme. Curie about the benefits of radioactive radiation from lightning arresters. After an examination of the theory of discharges during thunderstorms in conjunction with theories about radioactivity, discharge currents and voltages in such circumstances, the Swiss article concludes that radioactive transmitters are of no real benefit.

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246. (**)

AUTHORS Somerville, I. C.; Farish, O.; Tedford, D. J.

TITLE The Influence of Atmospheric Negative Ions on the Statistical Time Lag to Spark Breakdown

TYPE conference

PAGE 137-144

BOOK Gaseous Dielectrics IV - Proceedings of the Fourth International Symposium on Gaseous Dielectrics

PUBLISHER Edited by L. G. Christophorou and M. O. Pace, Pergamon Press, New York

CONFERENCE Fourth International Symposium on Gaseous Dielectrics

LOCATION Knoxville, Tennessee, USA

DATE May 29, 1984

KEYWORD experiment; air breakdown; negative ions; time lag

LANGUAGE English

ABSTRACT This paper reports measurements of the statistical time-lag to spark breakdown for sphere-sphere electrodes in atmospheric air. The results indicate a clear correlation between the natural small negative ion population and the measured time-lag distribution. From these and other observations it is concluded that the major source of initiatory electrons, for these particular experiments, is by the detachment of electrons from small negative ions.

COMMENT: This paper is relevant to lightning because the primary mechanism for initiation of an upward streamer for normal negative lightning is expected to be electron detachment of negative ions in the air near the lightning terminal tip. The results of this work imply a significant influence of humidity. The paper was published together with discussion and response to questions raised by G. Berger, R. J. Van Brunt, and S. M. Spyrou.

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247. (**)

AUTHORS Stahmann, J. R.

TITLE Launch Pad Lightning Protection Effectiveness

TYPE report

SPONSOR National Aeronautics and Space Administration

DATE Aug. 1, 1991

NTIS N91-32627/2/XAB

KEYWORD model; protection zones; theoretical

LANGUAGE English

ABSTRACT Using the striking distance theory that lightning leaders will strike the nearest grounded point on their last jump to earth corresponding to the striking distance, the probability of striking a point on the structure in the presence of other points can be estimated. The lightning strokes are divided into deciles having an average peak current and striking distance. The striking distances are used as radii from the points to generate windows of approach through which the leader must pass to reach a designated point. The projections of the windows on a horizontal plane as they are rotated through all possible angles of approach define an area that can be multiplied by the decile stroke density to arrive at the probability of strokes with the window average striking distance. The sum of all decile probabilities gives the cumulative probability for all strokes. The techniques

can be applied to NASA-Kennedy launch pad structures to estimate the lightning protection effectiveness for the crane, gaseous oxygen vent arm, and other points. Streamers from sharp points on the structure provide protection for surfaces having large radii of curvature. The effects of nearby structures can also be estimated.

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248. (**)

AUTHORS Standler, R. B.; Winn, W. P.

TITLE Effects of Coronae on Electric Fields Beneath Thunderstorms

TYPE journal

PAGE 285-302

JOURNAL Quarterly Journal of the Royal Meteorological Society

VOLUME 105

DATE 1979

KEYWORD measurement; corona; thundercloud; electric field; trees

LANGUAGE English

ABSTRACT

Intense electric fields beneath thunderstorms produce electrical discharges (coronae) at the tips of trees, bushes and other sharp objects attached to the surface of the earth. We find typical corona current densities of about 1 nAm^{-2} in an 8 kVm^{-1} field at ground. The ions released into the air limit the magnitude of the field at the ground to about 10 kVm^{-1}. Our measurements beneath thunderstorms with a balloon-borne electric field meter show that the magnitude of the field a hundred meters above the ground is several times larger than at the ground; in one case the field 300 meters above ground was 6 times that at the ground. The substantial thickness of the space charge layer and the speed with which it vanishes when the electric field strength declines imply that the charge carriers have substantial velocities (0.4 ms^{-1}) either because their mobilities are high or because they are carried by air motions.

Coronae also influence the time behavior of the electric field at the ground. The field at the ground often changes very rapidly after a lightning flash. The rate of change decreases as the field approaches the value it had prior to the flash. In contrast, the field a hundred meters above ground, which is often above most of the influence of space charge produced by coronae, increases more uniformly (linearly) during the time interval between lightning flashes. This behavior is similar to that of the field farther aloft in the interior of the cloud. Our numerical simulations of the shapes of recovery curves indicate that the corona current density is more accurately described by a cubic function than by a quadratic function of the electric field strength at the ground.

Despite strong influences of coronae, three properties of the field at the ground accurately reflect what happens above the space charge layer. First, the rapid changes in electric field during a lightning flash are not usually affected by corona space charge. Second, when the field at the ground is nearly constant, it usually has the same polarity as the field above the space charge layer. And third, when the field strength at the ground is nearly zero, and when certain other conditions are met, the time rate of change of the field at the ground is the same as that above the space charge layer.

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249. ( )

AUTHORS Stekol'nikov, I. S.
TITLE Study of Lightning and Lightning Protection
TYPE report
SPONSOR Foreign Technology Division, Wright-Patterson AFB
DATE Feb. 18, 1988
NTIS AD-A190 623/9/XAB
KEYWORD ball lightning; experimental; simulation
LANGUAGE English
ABSTRACT This Russian translation deals primarily with ball lightning including laboratory methods for making ball lightning. Brief sections discuss luminous clouds and 'Black' lightning. A table of contents for the entire book is also included.

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250. (**)

AUTHORS Suzuki, T.; Miyake, K.; Kishizima, I.
TITLE Lightning Strokes to Transmission Lines and Substations. I. Laboratory Experiments of Lightning Strokes
TYPE report
LOCATION Tokyo, Japan
SPONSOR Central Research Institution of Electric Power Industries
DATE Dec. 1, 1978
KEYWORD experimental; simulation evaluation; laboratory tests
LANGUAGE English
ABSTRACT Investigates lightning strokes to transmission lines and substations with comparison with long laboratory sparks. This report presents the results of long laboratory sparks, compares them with lightning strokes and discusses the possibility of the simulation of lightning by laboratory experiments.

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251. (***)

AUTHORS Suzuki, T.; Miyake, K.; Kishizima, I.
TITLE Study on Experimental Simulation of Lightning Strokes
TYPE journal
PAGE 1703-1711
JOURNAL IEEE Transactions on Power Apparatus and Systems
NUMBER 4
DATE April 1981
KEYWORD experimental; simulation evaluation; laboratory tests
LANGUAGE English
ABSTRACT This study reports on the possibility and the limitation of the experimental simulation of lightning discharges. Discharges in long air gaps with impulse voltages were investigated with multiple techniques. The features of long gap discharges were compared with those of lightning discharges. It is impossible to simulate the whole process of lightning discharges by laboratory experiments with conventional lightning or switching impulses. The possibility of the simulation remains only in the final stage of lightning strokes to the ground. The scale factor was introduced to relate a laboratory spark with the final lightning stroke.

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252. (**)

AUTHORS Szpor, S.
TITLE Relaxation Theory of the Lightning Stepped Leader
TYPE journal
PAGE 1293-1296
JOURNAL Bulletin de l'Association Suisse des Electriciens
VOLUME 68
NUMBER 24
DATE Dec. 1977
KEYWORD basic; model; relaxation theory; theoretical
LANGUAGE French
ABSTRACT The paper presents the relaxation theory of the lightning or very long spark stepped leader. The importance of converting relatively cold streamer to very hot plasma channel is explained and the need for a sufficiently high current to perform this conversion is pointed out. Charge distribution along the leader illustrates the theory and explains low amplitude of current fluctuations.

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253. (**)

AUTHORS Szpor, S.
TITLE Review of the Theories of the Lightning Main Discharge
TYPE journal
PAGE 279-290
JOURNAL Archiwum Elecktrotechniki
VOLUME 26
NUMBER 2
DATE 1977
KEYWORD basic; review; theoretical
LANGUAGE English
ABSTRACT First a trivial theory of the main lightning discharge is remembered, taking account the capacity and the inductivity. The corona or cold streamer layers around the hot plasma channel are responsible partially for values of the velocity v smaller than the light velocity c. A study of the field radiated inside the return component is carried out. The magnetic component of this field is shown to limit the velocity v. Surge currents are calculated for different velocities and different voltages. The variable resistance of the spark is discussed after Lundholm as an additional factor decreasing the velocity v. It is discussed that the surge impedance of the lightning return component is most probably of about 600 - 1500 ohms. This impedance may be studied experimentally using the surge reflections in some schemes. The front of the surge current is attributed to the antileader mechanism. The variable resistance of the spark may also play some part. The third factor of the current front is shown to be the filter mechanism connected with the branches.

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254. (***)

AUTHORS Szpor, S.
TITLE Lightning Protection Zones
TYPE journal
PAGE 561-577
JOURNAL Archiwum Elektrotechniki (Warsaw)
VOLUME 28
NUMBER 3
DATE 1979
KEYWORD antileaders; corona; protection zones; streamer cutoff; theoretical
LANGUAGE English
ABSTRACT This paper discusses concepts of protective zones in lightning protection and presents a critical review of theoretical and laboratory methods for determining these zones. Information about new environmental studies is presented. The influence of corona, streamer cutoff, and antileaders is discussed and the working-voltage effect is explained, particularly for UHV lines.

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255. (*)

AUTHORS Szpor, S.
TITLE Comparison of Polish Versus American Lightning Records
TYPE journal
PAGE 646-652
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS-88
NUMBER 5
DATE May 1969
KEYWORD survey; lightning; current crest values
LANGUAGE English
ABSTRACT A complete extension of [1] assemble 50 curves of the percentage frequencies against crest values of the lightning currents. These curves are collected from 35 publications and from numerous letters exchanged with research workers. However, only about 30 curves could be presented in this paper. We chose all available American curves and two curves from the Polish most precise records. Polish curve 1' is presented as relatively precise. The oldest American results are spoiled by enormous errors. Four sources of errors had been stated in [1], and two others have been presently added. Old current values are frequently too small by a factor of about 2. Nevertheless, some American curves are not far from the Polish curves. Corrections have been applied to the most important American curves. Afterwards a comparison of curves for the rates of the rise of lightning currents obtained in Poland, in the U.S.A., and in some other countries have been presented. Values about 100 kA/micro-second are not rare in Poland. Several causes of great errors in former values which were too small have been explained. Some controversies and doubts have been dealt with. Some newer results conform with the Polish curve.

[1] S. Szpor, E. Wasilenko, J. Samula, E. Dytkowski, J. Suchocki, and B. Zaborowski, CIGRE, Paper 319, 1964.

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256. (**)

AUTHORS Szpor, S.; Turkowski, W.
TITLE Laboratory Corroboration of the Relaxation Theory of the Lightning Stepped Leader
TYPE journal
PAGE 405-407
JOURNAL Archiwum Elektrotechniki
VOLUME 17
NUMBER 2
DATE 1968
KEYWORD experimental; model; relaxation theory; theoretical
LANGUAGE English
ABSTRACT A confirmation of the relaxation theory of the lightning stepped leaders by means of high speed photography of the surface spark in laboratory conditions is presented. The length of the spark was 3.44 m, the surge voltage was 160 kV, the number of steps was 7 or 8, the length of one step approximately = 43 cm, and the time between steps was about 1.7 μs. The cold plasma channel had a gradient of some 3.7 kV/cm. The experiments confirmed that the light of the step decreased towards the end of the travel in conformity with the relaxation theory.

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257. (*)

AUTHORS Takahashi, T.; Suginuma, Y.
TITLE Effect of Ground Structure on Impulse Discharge
TYPE conference
PAGE 401-404
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD basic; experimental
LANGUAGE English
ABSTRACT Effects of the ground soil condition to the impulse discharge were investigated to learn about the human and equipment safety in lightning disasters. Experiments were carried out with various ground soil conditions. The discharge modes that arise on the ground mainly can be classified into three types. The streamer velocity on the soil electrode was also shown.

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258. (*)

AUTHORS Takaki, K.; Akiyama, H.; Maeda, S.
TITLE Basic Experiments of Triggered Lightning Using a Water Jet
TYPE conference
PAGE 285-288
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan

SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; triggered; water jet
LANGUAGE English
ABSTRACT A new method to trigger lightning by a water jet is proposed and investigated experimentally by using an impulse generator. It was found from basic experiments that the flashover voltage decreased considerably as the length of the water jet between electrodes was increased. The decrease of the voltage by the water was equal to the decrease in the case of using a metal conductor instead of jetted water. One of the systems to produce water jets was composed of a water chamber and a high pressure air cylinder. A 40 m height of water jet was produced by using this system

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259. (*)
AUTHORS Takeno, H.; Cho, M.; Ohta, K.; Nakamoto, S.; Araki, K.
TITLE Basic Experiment on Extinction of Lightning by Laser Induced Discharge in Cloud
TYPE conference
PAGE 293-296
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; laser; model; plasma channel; theoretical
LANGUAGE English
ABSTRACT Laser-produced plasma in atmospheric air with vapor is studied experimentally and theoretically for the purpose of basic research on extinction of lightning in a cloud. By using an image processing system, temporal evolution of laser-produced plasma is measured, and its expansion and decay are studied from the emission intensity. The spatial distribution of emission intensity is compared with the numerical calculation of shock wave. Good agreement is obtained in the expanding phase. However, the theoretical model in the decay phase is not enough to explain the experimental results.

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260. (**)
AUTHORS Takeuti, T.; Hashimoto, T.; Takagi, N.
TITLE A Computer Simulation of Lightning Stepped Leader Strikes to Towers
TYPE conference
PAGE 265-267
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD basic; model
LANGUAGE English
ABSTRACT A stepped leader to the ground under cloud base is modelled on the basis of photographs of ground discharges without any consideration of accompanying electrical phenomena.

Using this model, lightning strikes to towers are simulated. The simulation indicates that a final jump distance between the tip of leader and the top of tower plays an important role for the occurrence probability of a lightning strike to the tower. Further, the simulation implies the shielding effect by the tower to ground discharge depends on the final jump distances.

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261. (**)

AUTHORS Teer, T. L.; Few A. A.
TITLE Horizontal Lightning
TYPE journal
PAGE 3436-3441
JOURNAL Journal of Geophysical Research
VOLUME 79
NUMBER 24
DATE August 20, 1974
KEYWORD observations; lightning; horizontal propagation; statistical analysis
LANGUAGE English
ABSTRACT Studies of the dissipating stage of a thunderstorm indicate that for the storm under investigation both cloud-to-ground (GC) lightning flashes and intracloud (IC) lightning flashes possess an extensive horizontal structure inside the cloud. The configurations of all lightning flashes, 17 CG events and 20 IC events, that occurred in the 30-min time interval preceding the end of significant electrical activity of a thunderstorm have been mapped. Lightning channel reconstructions were derived from analysis of thunder recorded by an array of microphones. Results indicate that the structure of IC lightning and the intracloud portions of CG lightning may be modeled as being contained in an ellipsoid whose long axis is parallel to the earth's surface. A typical ratio of long horizontal axis to short horizontal axis to vertical axis is 3:2:1. The results indicate that horizontal lightning structures are more persistent and extended than have been estimated from observations of the electric field. The most striking feature of the IC events and of the intracloud portions of the CG events is their marked tendency to align themselves along the same direction.

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262. (**)

AUTHORS Thanh, L. C.
TITLE Negative Corona in a Multiple Interacting Point-to-Plane Gap in Air
TYPE journal
PAGE 518-522
JOURNAL IEEE Transactions on Industry Applications
VOLUME IA-21
NUMBER 2
DATE March/April 1985
KEYWORD experiment; corona; streamer; electrode geometry; air breakdown
LANGUAGE English
ABSTRACT Negative corona discharge from multiple interacting points has been investigated with emphasis on the role of negative streamers in causing spark breakdown. The interaction

among the evenly spaced bright discharge spots existing along a negative corona wire was simulated with a multiple point electrode whose point-to-point spacing was adjustable. The points were arranged in a circular and linear pattern. Although the current-voltage characteristic curves for the multiple point electrode-to-plane geometry are different from that for a single point-to-plane, the sparkover voltages are the same for both geometries. Additionally, sparking was always observed between the central discharge point and the ground plate. The dependence of the corona current on the configuration of the cathode, the effects of streamer branching on the sparkover, and the breakdown voltage versus gap length relation will be discussed. The experimental results confirm that negative streamers are less dominant than positive streamers in affecting spark breakdown.

COMMENT: The results of this work are apparently consistent with the expectation that once a corona discharge has fully developed, the breakdown of air is influenced more by the local corona-produced space-charge distribution and less by the details of the electrode geometry.

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263. (**)

AUTHORS Thione, L.

TITLE The Dielectric Strength of Large Air Insulation

TYPE book

PAGE 165-205

BOOK Surges in High-Voltage Networks

PUBLISHER Edited by Klaus Ragaller, Plenum Press, New York

DATE 1980

KEYWORD review; air breakdown; streamer; electron avalanche; corona inception; leader

LANGUAGE English

ABSTRACT The paper deals with the dielectric strength of air insulation in the light of the more recent knowledge of the physics of air discharge, in order to show how the behavior of the insulation may be explained, interpreted and, to some extent, predicted on the basis of a physical approach. In this respect the paper firstly presents a short review of the basic mechanisms of discharge, and gives evidence for the relation between the various stages of the discharge and the statistical nature of the breakdown phenomena. The predetermination of the corona-inception voltage is briefly examined as depending on electrode geometry, voltage waveform and polarity, electrode-surface conditions and atmospheric conditions. Methods used to evaluate breakdown voltage are reviewed, as applicable to different types of voltages: switching impulse, lightning impulse, a.c. and d.c. The role played by the main influencing factors, such as electrode geometry, voltage shape and polarity, is examined as well as those resulting from backflashovers, intervention of surge arresters, etc. Experimental results are presented in order both to illustrate the general properties outlined and to show the validity and limits of the prediction methods, with regard to UHV air clearances and considering, besides elementary laboratory gaps, typical line and substation insulation.

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264. (*)

AUTHORS Thomson, E. M.

TITLE Characteristics of Port Moresby Ground Flashes

TYPE journal

PAGE 1027-1036

JOURNAL Journal of Geophysical Research

VOLUME 85

NUMBER C2

DATE Feb. 20, 1980

KEYWORD observations; lightning; statistics; stepped leader; photography; current; interstroke interval

LANGUAGE English

ABSTRACT An investigation into the characteristic features of lightning flashes to ground in Port Moresby, Papua New Guinea (latitude 9 degrees S, longitude 147 degrees E), has been carried out. A scheme is presented for the identification of discharge features from simultaneous records of optical radiation, electric field change, and HF radiation. Data were obtained from records of 80 identified ground flashes comprising 282 strokes, 202 interstroke intervals, 223 continuing currents, and 53 stepped leaders. Flash durations are log normally distributed with a geometrical mean of 604 ms and a standard deviation of 0.25 decade. Sixty-eight per cent of pre-first stroke processes had durations exceeding 100 ms, the mean being 240 ms. Of 59 flashes outside the reversal distance electric field, records of 80% indicated that negative charge was raised before the first return stroke. The distribution of stepped leader durations is normal with a mean of 21 ms and standard deviation of 8 ms. Interstroke intervals are approximately log normally distributed, with a geometrical mean of 61 ms and a standard deviation of 0.36 decade. The geometrical mean value of continuing current duration is 5.5 ms and the standard deviation 0.70 decade, but the distribution is neither normal nor log normal. Of 34 multiple stroke flashes, 47% have at least one long continuing current. The form of the frequency distribution of continuing current duration may reflect a fundamental distinction between long and short continuing currents: however, it is probably the result of differences between the 1976 and 1977 distributions.

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265. (*)

AUTHORS Thottappillil, R.; Uman, M. A.

TITLE Lightning Return Stroke Model with Height-variable Discharge Time Constant

TYPE journal

PAGE 22773-22780

JOURNAL Journal of Geophysical Research

VOLUME 99

NUMBER D11

DATE Nov. 20, 1994

KEYWORD lightning; model; leader; return stroke

LANGUAGE English

ABSTRACT A new lightning return stroke model is proposed in which the lightning channel, previously charged by the leader, is exponentially discharged with the discharge time constant being a general function of height. The new model is both more physically reasonable than the Diendofer-Uman model (Diendofer and Uman, 1990) and its

modification by Thottappillil et al. (1991). In the new model a single height-variable discharge time constant is used instead of the two height-invariant discharge time constants used for natural lightning in the Diendorfer-Uman model. As an illustration of the use of the new model, the measured electric fields for three triggered lightning return strokes about 5-km distant are compared with fields calculated from the model, using simultaneously measured channel base current and return stroke speed as inputs to the model.

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266. (***)

AUTHORS Thum, P. C.; Liew, A. C.; Wong, C. M.
TITLE Computer Simulation of the Initial Stages of the Lightning Protection Mechanism
TYPE journal
PAGE 4370-4377
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS101
NUMBER 11
DATE Nov. 1982
KEYWORD Franklin rod; model; upward streamers
LANGUAGE English
ABSTRACT The paper describes a computer program developed for the study of the growth of corona streamers from a lightning rod. The basic physical processes of electrical discharge are applied in the model. From results of computer studies, it was found that the determination of striking distance cannot rely solely on the state of growth of the upward streamer. The attractive effect of the lightning rod should be measured in terms of the rate of descent of the leader stroke with respect to the growth of the upward streamer. Additional studies were also made to determine the effect of structure height on striking distance.

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267. (*)

AUTHORS Trichel, G. W.
TITLE The Mechanism of the Point-to-Plane Corona in Air at Atmospheric Pressure
TYPE journal
PAGE 382-390
JOURNAL The Physical Review
VOLUME 55
DATE 1939
KEYWORD experiment; corona; streamer; space charge
LANGUAGE English
ABSTRACT Attention is called to the fluctuating character of the current in the positive point-to-plane corona in air at atmospheric pressure. It is shown that in self-sustaining corona the current is due to a large number of individual current-pulses or bursts which are distributed over the surface of the point in regions of adequate field strength. The bursts of current are quite random in time, space, and intensity, and in general are composed of many successive avalanches of electron ionization which flow into regions of high field strength caused by space charges left by preceding avalanches. These bursts propagate

outward across the gap until extinguished by space charge accumulations, diffusion, self-repulsion, and ion migration in the field as well as by infelicitous coincidences of avalanche and the space charge distribution in the gap. The succeeding electron avalanches are initiated in air by photo-electrons produced in the gas ahead of the point. Evidence of an electrical, visual, and photographic character is presented confirming the existence of bursts and giving orders of magnitude of various features under operating conditions. The ionization produced is most intense at the point in the early stages and the number and intensity of the bursts increase with field strength. The development of a burst at one spot is exceedingly rapid (about 10^{-8} sec.) and is followed by a longer period (of about 10^{-6} sec.) as regards that spot, in which the field clears the space charge. In air it appears that the self-sustaining corona requires a high enough potential to overcome the space charge, an adequate current to furnish photo-electrons, in addition the formation of negative ions to insure that fluctuations shall not break off the discharge. As both the field at the point and clearing field increase, the bursts propagate further into the gap and ultimately form streamers from 6 to 11 mm long. When these catch up with previous extinct space charge streamers further out in the gap, they project themselves further towards the cathode much in the manner of the leader strokes in lightning discharge. If such a streamer striking the cathode creates an active cathode spot the return discharge produces a spark or an arc.

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268. (**)

AUTHORS Turkowski, W.
TITLE Study of the Long Sliding Spark
TYPE journal
PAGE 279-295
JOURNAL Archiwum Elektrotechniki
VOLUME 30
NUMBER 1
DATE 1981
KEYWORD basic; experimental; model
LANGUAGE Polish
ABSTRACT About 850 records of sparks by lightning and switching surges of both polarities were recorded in Polish laboratories. Development mechanisms of the leader of very long sliding spark by lightning and switching surges have been determined. Approximate values of leader parameters have been evaluated, i.e. average speed of streamer and leader, the charge carried away and the given off energy. Temperature of streamer and plasma channel by lightning surges was also evaluated. A summary in English is included.

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269. ( )

AUTHORS Twomey, R. C.
TITLE Effects of Laboratory Simulated Precipitation Static Electricity and Swept Stroke Lightning on Aircraft Windshield Subsystems
TYPE report
SPONSOR Douglas Aircraft Company, Long Beach, CA

DATE July 1, 1976
NTIS AD-A037 196/3
KEYWORD aircraft; practical; simulation; swept stroke lightning
LANGUAGE English
ABSTRACT Candidate outer ply materials for aircraft windshields subjected to laboratory simulated static electric charging and swept stroke lightning tests are evaluated. Very high values of static charge can accumulate on the outer insulating surface of a windshield. Electrical discharging can occur, usually in the form of surface flashing. The discharge generates electrical transients which might cause electromagnetic interference and damage to electrical components, depending on the system and component design. Methods of generating the electrostatic charge for test purposes and the control and evaluation of the discharges are covered. Potential damage to aircraft windshields from swept stroke lightning is evaluated by subjecting test specimens to man-made lightning. Recommendations are included which should enable the design of windshield systems that are more immune to the effects of precipitation static charging and swept stroke lightning. A study of the effects of nuclear electromagnetic pulse (EMP) in windshield design was added to the contract, with the results included in an appendix to this report.

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270. (*)
AUTHORS Uchida, S.; Shimada, Y.; Yamanaka, C.; Fujiwara, E.; Izawa, Y.; Yamanaka, T.; Nakai, S.; Wang, D.; Kawasaki, Z. I.; Matsuura, K.; Nagai, T.; Sonoi, Y.; Shimokura, N.
TITLE Laser Triggered Lightning Experiments in the Laboratory
TYPE conference
PAGE 313-316
CONFERENCE 8th International Symposium on High Voltage Engineering Proceedings, vol. 3
LOCATION Yokohama, Japan
SPONSOR IEE of Japan
DATE Aug. 23, 1993
KEYWORD experimental; laser; plane-plane gap; simulation; triggered
LANGUAGE English
ABSTRACT Laser induced lightning experiments are carried out using a TEA CO_2 laser with an output energy of ~100 Joules to investigate the feasibility of field experiments. A 8.5 m long laser induced flashover had been achieved by using a new type of focusing mirror. The flashover voltages are -1.1 MV and -0.7 MV for plasma lengths of 8.5 m and 7.5 m, respectively. The leader propagation and flashover process induced by laser have been measured by a streak camera. A stepped leader that is similar to the stepped leader progression in natural lightning appears in the laser induced flashover. The flashover electric field induced by laser plasma was measured in a plane-plane electrode configuration. The measured field is 0.6 MV/m and found to be smaller than the self breakdown field of 3 MV/m.

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271. (**)

AUTHORS Uman, M. A.; Beasley, W. H.; Tiller, J. A.; Lin, Y.; Krider, E. P.; Weidmann, C. D.; Krehbiel, P. R.; Brook, M.; Few, A. A. Jr.; Bohannon, J. L.; Lennon, C. L.; Poehler, H. A.; Jafferis, W.; Gulick, J. R.; Nicholson, J. R.

TITLE An Unusual Lightning Flash at Kennedy Space Center

TYPE journal

PAGE 9-16

JOURNAL Science

VOLUME 201

NUMBER 4350

DATE July 7, 1978

KEYWORD observation; lightning; electric-field measurement; radar; return stroke

LANGUAGE English

ABSTRACT A lightning flash that struck the 150-meter weather tower at Kennedy Space Center was studied by several research groups using various techniques. The flash had unusually large peak currents and a stepped leader of relatively short duration. The charged regions neutralized by the three return strokes were located within a horizontal layer between heights of about 6 and 8 kilometers, where environmental temperatures were about -10 to -20 °C. The charge source for the first return stroke coincided with a vertical shaft of precipitation inferred to have been graupel or hail. Charge sources for subsequent strokes were near the edge of the detectable precipitation echo. The overall channel length was about 10 kilometers. A vertically oriented intracloud discharge occurred after the three return strokes.

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272. (**)

AUTHORS Uman, M. A.

TITLE Natural Lightning

TYPE journal

PAGE 785-790

JOURNAL IEEE Transaction on Industry Applications

VOLUME 30

NUMBER 3

DATE 1994

KEYWORD review; model; basic

LANGUAGE English

ABSTRACT The present understanding of natural lightning is reviewed. Recent research on lightning has been motivated, in part, by the need to protect advanced ground-based and airborne systems that utilize low-voltage, solid-state electronics; by the desire to prevent spectacular accidents, such as occurred in 1969 during the launch of Apollo 12 and in 1987 during the launch of Atlas-Centaur 67; and by the desire to elucidate the physics of one of nature's most impressive phenomena.

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273. (**)

AUTHORS Uman, M. A.

TITLE A Comparison of Natural Lightning and the Long Laboratory Spark with Application to Lightning Testing

TYPE report

SPONSOR Westinghouse Research Labs, Pittsburgh, PA

DATE Aug. 1, 1970

NTIS AD-712 308

KEYWORD practical; simulation; simulation evaluation;

LANGUAGE English

ABSTRACT Laboratory sparks a few meters in length can be used to simulate lightning current rates-of-rise and peak values and to simulate some of the temporal characteristics of the lightning channel temperature. Long spark generators are inadequate for producing a simulation of the continuing current phase of lightning. Long sparks cannot be used to produce a simulation of the shock wave due to lightning except in that the spark data can be scaled by theory to predict the characteristics of the lightning shock wave. A short discussion is given of the several types of lightning which might be encountered by an aircraft. The validity of long-spark testing in determining the likely points of strike of a lightning discharge to an aircraft or other structure is briefly considered.

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274. (***)

AUTHORS Uman, M. A.

TITLE The Lightning Discharge

TYPE book

VOLUME 39

PUBLISHER Academic Press, Inc., New York, NY

DATE 1987

KEYWORD review; lightning; history; physics

LANGUAGE English

ABSTRACT COMMENT: This is a valuable reference book that provides a comprehensive review of the current understanding and theories about the lightning discharge and includes many references to publications of results from scientific studies on lightning.

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275. (*)**

AUTHORS Uman, M. A.; Krider, E. P.

TITLE A Review of Natural Lightning: Experimental Data and Modeling

TYPE journal

PAGE 79-112

JOURNAL IEEE Transactions on Electromagnetic Compatability

VOLUME EMC-24

NUMBER 2

DATE May 1982

KEYWORD lightning, experimental data, review, modeling

LANGUAGE English

ABSTRACT

A critical review is presented of the currents and the electric and magnetic fields characteristic of each of the salient discharge processes which make up cloud-to-ground and intracloud lightning. Emphasis is placed on the more recent work in which measured waveform variation is in the microsecond and submicrosecond range, since it is this time-scale that is of primary importance in lightning/aircraft interactions. The state of the art of the modeling of lightning currents and fields is discussed in detail. A comprehensive bibliography is given of all literature relating to both lightning measurements and models.

COMMENT: One important aspect of this work is that it includes 550 references to published work on lightning up to 1982. Most of the cited works have to do with physical phenomena such as radiation emission associated with lightning. Although most of the references are not directly relevant to lightning protection, there is a section on the lightning attachment process. Most of the references in that section are also included in the present bibliography.

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276. (*)

AUTHORS Van Brunt, R. J.

TITLE Physics and Chemistry of Partial Discharge and Corona - Recent Advances and Future Challenges

TYPE Journal

PAGE 761-784

JOURNAL IEEE Transactions on Dielectrics and Electrical Insulation

VOLUME 1

NUMBER 5

PUBLISHER IEEE

DATE 1994

KEYWORD corona; theory; experiment; review

LANGUAGE English

ABSTRACT

Results of recent research on physical and chemical processes in partial discharge (PD) phenomena are reviewed. The terminology used to specify different types or modes of PD are discussed in light of a general theory of electrical discharges. The limitations and assumptions inherent to present theoretical models are examined. The influence of memory propagation effects in controlling the stochastic behavior of PD is shown. Examples of experimental results are presented that demonstrate the nonstationary characteristics of PD which can be related to permanent or quasi-permanent discharge-induced modifications (aging) of the site where the PD occur. Recommendations for future research are proposed.

COMMENT: Evidence is provided in this work that the corona discharge that occurs at the tip of a metal rod is an enormously complex stochastic process in which the statistical properties are governed by memory propagation effects coupled to field-dependent discharge initiation probability.

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277. (*)

AUTHORS Van Brunt, R. J.; Kulkarni, S. V.

TITLE Stochastic Properties of Trichel-pulse Corona: A non-Markovian Random Point Process

TYPE journal

PAGE 4908-4932

JOURNAL Physical Review A

VOLUME 42

NUMBER 8

DATE Oct. 15, 1990

KEYWORD experiment; theory; corona; stochastic behavior

LANGUAGE English

ABSTRACT The stochastic properties of negative, point-to-plane, Trichel-pulse corona discharges are completely characterized in terms of a set of measured conditional and unconditional discharge pulse-amplitude and pulse-time-separation distributions. The Trichel-pulse phenomenon is shown to be a clear example of a non-Markovian, marked random point process in which memory effects play an important role. Strong correlations are shown to exist among the amplitudes and time separations of successive discharge pulses that indicate how initiation and growth of a discharge pulse are affected by the presence of residual ion space charge and metastable species from previous pulses. The analysis required to assess consistency among the various measured probability distributions is discussed and used to interpret observed variations in distribution profiles. Because of the observed dependence of discharge pulse amplitude on both the amplitude of and time separation from the previous pulse, memory can propagate indefinitely back in time. The experimental limitations to verifying the extent of memory propagation are analyzed.

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278. (***)

AUTHORS Varela, M. D.

TITLE The Radioactive Lightning Conductor

TYPE journal

PAGE 115-120

JOURNAL Revista Electrotecnica

VOLUME 75

NUMBER 3

DATE May-June 1989

KEYWORD critique; radioactive rod; review

LANGUAGE Spanish

ABSTRACT The idea of the radioactive lightning conductor as an improvement upon Franklin's system goes back to a proposal by Szillard in 1914. In Argentina work has been done on it since the 1960's. The author traces the history of the notion, notably the work of Muller-Hillebrand and of Baatz, and the conclusions of the international conference on lightning in Yugoslavia in 1974. The author discusses questions of the possible danger and the legal permissibility of the use of radioactive materials for this purpose. This concurs with the generally accepted view that the addition of radioactive components to standard forms of lightning conductors is of no value.

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279. (*)

AUTHORS Vonnegut, B.
TITLE The Atmospheric Electricity Paradigm
TYPE journal
PAGE 53-60
JOURNAL Bulletin of the American Meteorological Society
VOLUME 75
NUMBER 1
DATE Jan. 1994
KEYWORD review; lightning; thundercloud development
LANGUAGE English
ABSTRACT Remarkable aspects of the thundercloud are its intense electrification, participation, and convection. A satisfactory understanding of how a thunderstorm works will require a continuing series of investigations to explore the complicated interrelationships among these phenomena. Until now the major effort has been devoted to studies of how precipitation causes electrification. For a century, investigations of thunderstorms have been dominated by the idea that lightning is produced by a charge-separation process within the cloud caused by falling precipitation. The origin of this idea, its implications, present status, and probable future are examined in the light of T. S. Kuhn's views on the nature of scientific progress. Despite some achievements, the results of research based on the precipitation theory have proved disappointing. For example, they have shed little light on important problems such as the factors that determine the polarity of the cloud electric dipole and the role that electricity plays in meteorological processes. During this century, with the discovery of cosmic rays and the ionization they produce in the air above the cloud, it has become apparent that other processes which do not involve contact charge separation or falling precipitation, are also causing electrification. Thunderstorms exercise great influence, for both good and bad, on many human activities. In view of their great environmental importance, it is surprising how little is known about them and how little effort is being made to understand how they work. It is urged that the present limited thunderstorm research activities be expanded to include new, and possibly more productive, approaches.

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280. (*)

AUTHORS Wagner, C. F.
TITLE The Relation Between Stroke Current and the Velocity of the Return Stroke
TYPE journal
PAGE 609-617
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME 82
DATE October 1963
KEYWORD laboratory tests; analysis; lightning; return stroke; velocity
LANGUAGE English
ABSTRACT The velocity of the return stroke is an important element in estimating (1) the surge impedance of the return stroke, (2) the potential of the downward leader, and (3) the length of the last striking distance. The energy required to establish an arc plasma can be determined from laboratory tests. By equating this quantity to the energy required to retard the velocity of a traveling wave, the consequent velocity of the return stroke can be evaluated in terms of the stroke current.

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281. (***)

AUTHORS Wagner, C. F.; Hileman, A. R.
TITLE The Lightning Stroke
TYPE journal
PAGE 229-242
JOURNAL Transactions of the American Institute of Electrical Engineers, Part III
VOLUME 77
DATE June 1958
KEYWORD review; streamers; stroke mechanism; leader; corona; theory
LANGUAGE English
ABSTRACT COMMENT: The authors review the available statistical information about measured lightning stroke waveforms and the correlation between measured crest current and time to crest. They argue that upward leaders are more likely to develop from towers and ground wires than from ground level and note that at the present state of the art, the conditions under which upward streamers develop is not completely understood. The existence of such streamers have been verified by photographs in a few isolated instances. It is also argued that, since the charge lowered by the downward leader appears to increase with the discharge current that is subsequently developed by the charge, the lengths of the ground leaders are longer the greater the subsequent discharge current. The results presented in this work suggest that there can be significant statistical variability in the ground leader length.

In the conclusion it is stated that the transient arc characteristics of the return stroke are such as to introduce a series voltage in the arc path that is proportional to the rate-of-change of the current and which, therefore, has the characteristics of an inductance. The inductance together with the natural inductance and corona capacitance, which is determined by a charge located at a greater radius than the current, helps to explain that the velocity of propagation of the return streamer is less than that of light. Laboratory tests on the corona sheath surrounding a conductor indicate a time lag of the order of 0.1 to 0.2 μs. Extrapolating this time lag to the scale met in lightning, on the assumption that the lateral process of the discharge from the arc to the tapped charge area is by streamer propagation, would result in a time to crest of the current of 1 to 2 micro-seconds or more. As the head of the return streamer reaches a particular point, the charge fed into the streamer at that point increases abruptly to half of its final value and rises to crest more slowly.

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282. (**)

AUTHORS Wagner, C. F.; Hileman, A. R.
TITLE Mechanism of Breakdown of Laboratory Gaps
TYPE journal
PAGE 604-622
JOURNAL Transactions of the American Institute of Electrical Engineers, Part III
VOLUME 80
DATE Oct. 1961
KEYWORD review; experiment; air breakdown; lightning simulation
LANGUAGE English

ABSTRACT The authors' primary interest in the mechanism of gap breakdown is in its relation to lightning stroke phenomena. In considering the effect of the lightning stroke upon transmission lines, the problem has been resolved into two parts. The first of these is the electrical response of the line to specific assumed stroke characteristics. A method to determine this response was recently presented before the AIEE in which it was shown that the time change in the charge in the stroke above the tower may be as important as the current fed into the transmission line. The second part of the problem is the determination of those stroke characteristics that are required to implement this approach. An initial effort along this line was previously presented in which an attempt was made to synthesize the stroke characteristics by correlating the known stroke characteristics with laboratory determined characteristics of long sparks. A further effort was made to utilize the available information concerning the electric field produced at remote points to determine the wavefront of the stroke current. The purpose of this paper is to present a review of available information on laboratory produced sparks, to present new data on this subject, and to coordinate the external manifestations of gap breakdown from an engineering point of view. These results have been coordinated in a companion paper, in this issue, with similar data from natural lightning.

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283. (**)

AUTHORS Wagner, C. F.; Hileman, A. R.
TITLE The Lightning Stroke - II
TYPE journal
PAGE 622-642
JOURNAL Transactions of the American Institute of Electrical Engineers, Part III
VOLUME 80
DATE Oct. 1961
KEYWORD lightning stroke; leader; streamers; corona; model; laboratory tests
LANGUAGE English
ABSTRACT In a previous paper [C. F. Wagner and A. R. Hileman, AIEE Transactions, pt. III (Power Apparatus and Systems), Vol. 77, June 1958, pp. 229-42], similarly titled, the authors undertook to synthesize certain characteristics of the lightning stoke by applying and extrapolating the results of laboratory experiments. They were supported in this effort by data concerning the transient character of arcs and the properties of corona within cylindrical shells. A companion paper in this issue discusses the properties of laboratory-produced sparks and the present paper applies this information, together with additional data concerning natural lightning, to a more detailed consideration of the lightning stroke. A new mechanism of the leader steps is presented. Also, a theory of very important events that occur during the early stages of the return stroke is elucidated.

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284. (**)

AUTHORS Wagner, C. F.; McCann, G. D.
TITLE Lightning Phenomena
TYPE journal
PAGE 1-35
JOURNAL Electrical Engineering

DATE Aug.- Oct. 1941
PUBLISHER American Institute of Electrical Engineers, 33 West 39th Street, New York, NY
KEYWORD review; observations; lightning; surges; field studies; statistical distributions
LANGUAGE English
ABSTRACT Although Franklin conducted his famous lightning experiments about the middle of the 18th century, little more was learned until about a generation ago when lightning outages on expanding electric-power systems made an intensive study of the phenomena imperative. Many investigators in different parts of the world have studied lightning during that period, many special instruments have been devised for recording various characteristics of the phenomena, and from information obtained through the use of these instruments remedial measures have been devised - to the end that in spite of the continuously expanding network of electric-power lines, outages caused by lightning have been greatly reduced. In this series of three articles, the authors have reviewed and described: (1) the general characteristics of lightning, the accumulation of charge, and the mechanism of the discharge; (2) instruments available for measuring the properties of lightning; and (3) results of field investigations in which the instruments described in part 2 were used.

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285. (*)
AUTHORS Walko, L. C.; Hebert, J. L.
TITLE Lightning Simulation Facilities in the United States and Europe
TYPE conference
CONFERENCE 23rd Aerospace Sciences Meeting
LOCATION Reno, NV USA
SPONSOR AIAA
DATE Jan. 14, 1985
KEYWORD review; simulation; simulation facilities; simulation standards
LANGUAGE English
ABSTRACT The use of sophisticated avionics systems and non-metallic structures has enhanced aircraft susceptibility to, and the need for protection from, the lightning threat. Some lightning aspects may be simulated and this has established lightning simulation as a valuable aid in aircraft design. This paper describes the lightning threat and existing lightning simulation standards. It overviews lightning simulation facilities in the United States and Europe.

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286. (**)
AUTHORS Wang, M. C.; Kunhardt, E. E.
TITLE Streamer Dynamics
TYPE journal
PAGE 2366-2373
JOURNAL Physical Review A
VOLUME 42
NUMBER 4
DATE Aug. 15, 1990

KEYWORD streamer; model; theory
LANGUAGE English
ABSTRACT An analysis of streamers is presented from the viewpoint of the interplay of the rate processes that contribute to their development. The space-time evolution of a streamer front is described by a sequence of stages that are identified by the dominant rate process determining the local properties of the front and the "turning point" where this process is overcome by others. Numerical and analytical results are used to determine these stages. From this analysis, the properties of positive (cathode-directed) and negative (anode-directed) streamers are elucidated, in particular, the dynamics that lead to the saturation of electron-density and electric-field enhancement. An expression is obtained that relates the dynamics of the positive and negative streamers associated with an initial space-charge distribution.

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287. (**)
AUTHORS Watanabe, Y.
TITLE Switching Surge Flashover Characteristics of Extremely Long Air Gaps
TYPE journal
PAGE 933-936
JOURNAL IEEE Transactions on Power Apparatus and Systems
VOLUME PAS-86
NUMBER 8
DATE August 1967
KEYWORD laboratory tests; air breakdown; impulse; switching surge
LANGUAGE English
ABSTRACT The purpose of this paper is to estimate the limit of the possible transmission line voltage and to clarify the mechanism of discharge in air. Tests were performed on the switching surge flashover of long air gaps under dry conditions. The flashover voltages of the switching surge with duration of wave front 180 microseconds were obtained up to 13 meters for rod-plane gaps for positive polarity. The tests were performed at the Shiobara Outdoor Laboratory.

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288. (**)
AUTHORS Waters, R. T.
TITLE Lightning Phenomena and Protection Systems: Developments in the Last Decade
TYPE conference
PAGE 1.2:1-8
CONFERENCE Lightning Protection 92 - Buildings, Structures and Electronic Equipment Conference and Exhibition
LOCATION Leatherhead, UK
SPONSOR ERA Technology
DATE June 23, 1992
KEYWORD lightning protection; review
LANGUAGE English

ABSTRACT Recent years, which have seen the introduction of a new BS 6651 in 1985, have also given us significant physical research of the breakdown phenomenon. This has occurred both in the laboratory and the field, and the studies in Japan of both natural and triggered lightning are particularly notable. The emergence of electromagnetic compatibility as a main priority in commercial, military and aviation microelectronic equipment has provided a stimulus to research. This same digital technology has given lightning researchers and protection engineers better transient recording capability and modeling techniques. After a brief resume of classical lightning research, the author reports recent advances in the knowledge of the structure of positive and negative leaders, the corona phenomenon, the role of the upward leader, and statistical lightning models. The influence of these factors on the point of strike will be discussed. The very active worldwide research on metal oxide lightning arresters is also summarised.

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289. (**)

AUTHORS Waters, R. T.
TITLE Spark Breakdown in Non-uniform Fields
TYPE book
PAGE 385-532
BOOK Electrical Breakdown of Gases, Edited by J. M. Meek and J. D. Craggs
PUBLISHER John Wiley & Sons, Ltd., New York, NY
DATE 1978
KEYWORD review; long sparks; air; transient behavior; corona; impulse breakdown
LANGUAGE English
ABSTRACT COMMENT: This is an extensive review of research performed up to 1978 on electrical breakdown of gases, including air, in non-uniform field gaps. It covers sparkover characteristics of long air gaps relevant to laboratory lightning simulation including statistical properties, transient characteristics, effects of irradiation, and effects of atmospheric humidity. It also includes a comprehensive bibliography.

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290. ( )

AUTHORS Whitaker, M.
TITLE Activation of the Navy's Indirect Effects Lightning Simulation Laboratory
TYPE report
SPONSOR Naval Air Test Center, Patuxent River, MD
DATE Aug. 1, 1991
NTIS N91-32628/0/XAB
KEYWORD aircraft; practical; simulation
LANGUAGE English
ABSTRACT The Naval Air Test Center (NATC) is currently the Navy's lead lab for electromagnetic effects testing. As part of this charter, it has been performing lightning effects testing on Navy aircraft in support of specification compliance since 1973. An overview is presented of lightning test and evaluation efforts at NATC, both past and present, as well as its plans for the future. The array of simulation capabilities presently operational are described, and a high level look is given to the test methodology now being used. The principal discussion centers on the results from the recent air launched ordnance test and testing of the Navy's A-6E all weather attack aircraft. Particular attention is paid to the NATC's test approach, including details about coaxial return construction, aircraft preparation, and the test waveforms and data acquisition systems that were used.

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291. (*)

AUTHORS White, R. A.

TITLE Application of Pulsed Power in the Simulation of Severe Natural Lightning

TYPE report

SPONSOR Department of Energy, Washington, D.C.

NTIS DE85012866/XAB

DATE 1985

KEYWORD experimental; Marx generator; pulsed power; simulation

LANGUAGE English

ABSTRACT Pulsed-power technology has application in the laboratory simulation of severe natural lightning. Several years of successful lightning simulator operation at this facility have confirmed the value of pulsed-power approaches in safety assessment testing, and for evaluating lightning induced hazards and transient effects. Performance capability examples are presented to substantiate the practicality of using crowbarred Marx impulse generators for lightning simulation testing. Severe, double-pulse, direct-stroke environments with continuing current have been applied to full-size aircraft and a variety of other test items. A typical double-pulse test simulation of severe lightning has a first-current peak in excess of 200 kiloamps, a rise time of about one microsecond, and a half-amplitude pulse width of about 200 microseconds.

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292. (**)

AUTHORS Williams, E. R.; Cooke, C. M.; Wright, K. A.

TITLE The Role of Electric Space Charge in Nuclear Lightning

TYPE journal

PAGE 1679-1688

JOURNAL Journal of Geophysical Research

VOLUME 93

NUMBER D2

DATE Feb. 20, 1988

KEYWORD model; experiment; lightning propagation; space charge

LANGUAGE English

ABSTRACT The phenomenon of nuclear lightning is reexamined with theoretical models and laboratory-scale experiments. It is shown that the distribution of electric space charge, rather than the electric field alone, must be considered in accounting for the shapes and locations of nuclear lightning channels in the atmosphere. A self-consistent distribution of space charge requires a consideration of both electronic and ionic conduction in the irradiated atmosphere, in agreement with earlier findings (Grover, 1980). The magnitudes of nuclear lightning currents (10^5 - 10^6 A)(Colvin et al., 1987) are compatible with predictions for electrical conduction currents based on contemporary theory. Comparisons between the theoretical predictions and laboratory discharge experiments for nuclear lightning case emphasize the dominant influence of electric space charge on discharge paths in both solid insulators and thunderclouds.

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293. (**)

AUTHORS Williams, E. R.; Cooke, C. M.; Wright, K. A.
TITLE Electrical Discharge Propagation in and Around Space Charge Clouds
TYPE journal
PAGE 6059-6070
JOURNAL Journal of Geophysical Research
VOLUME 90
NUMBER D4
DATE June 30, 1985
KEYWORD experiment; model; space charge; lightning propagation
LANGUAGE English
ABSTRACT The electron trapping characteristic of a solid dielectric material (polymethylmethacrylate) is exploited to study electrical discharge propagation in laboratory-scale space charge clouds. Similarities with the static and dynamic behaviors of thundercloud electricity are identified, and a combination of theoretical and empirical scaling relationships enables a rough translation of parameters from laboratory scale to thundercloud scale. Applications of the laboratory technique to specific thunderstorm situations reinforce the value of discharge structure studies in exposing the very important space charge configuration that gives rise to lightning.

COMMENT: This experiment demonstrates the significant effect that space charge can have on the path of discharge propagation.

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294. (*)

AUTHORS Williams, E. R.
TITLE The Electrification of Thunderstorms
TYPE journal
PAGE 88-99
JOURNAL Scientific American
DATE November 1988
KEYWORD review; cloud charging mechanisms; corona; space charge
LANGUAGE English
ABSTRACT Although it has been known for two centuries that lightning is a form of electricity, the exact microphysical processes responsible for the charging of storm clouds remain in dispute.

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295. (**)

AUTHORS Woolner, P. G.
TITLE Calculating Lightning Protection Zones
TYPE report
SPONSOR The MITRE Corporation, 7525 Colshire Drive, Mclean, VA 22102-3481
NTIS MTR-89W00206
DATE 1990
KEYWORD applications; model; protection zones

LANGUAGE English

ABSTRACT Equations to calculate the zone of protection provided by lightning protection systems are derived from the concept of a minimum striking distance for the last leader step of a lightning flash. These equations and procedures for their use are applicable to all configurations of lightning rods and objects to be protected. The benefit provided by an isolated lightning rod reaches a maximum when the height of the rod equals the striking distance, but multiple rod systems with the correct spacing can be used to extend the protection volume to any desired amount. Initially developed for the National Oceanic and Atmospheric Administration satellite ground stations, the equations are applicable to any site requiring lightning protection. Examples show the practical application of the equations for a minimum striking distance of 100 feet. An analogy relating the striking distance to a large ball provides a useful aid to visualize the protected zones in complex situations, and in selecting the equations used to calculate the zone of protection. The concept also leads to recommended areas for future research.

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296. (*)

AUTHORS Yamabe, C.; Nakamura, K.; Horii, K.

TITLE Technology for Triggered Lightning by Laser Beam

TYPE journal

PAGE 718-721

JOURNAL Oyo Buturi

VOLUME 61

NUMBER 7

DATE July 1992

KEYWORD experimental; laser; triggered; ultraviolet

LANGUAGE Japanese

ABSTRACT Fundamental studies of laser-triggered lightning has recently attracted much attention as a technology of post rocket-triggered lightning. Both strongly and weakly ionized plasma channels have been proposed to be used for this technology. In this report, the latter case which is produced by ultraviolet laser beams such as N_2 laser, XeCl and KrF excimer lasers is introduced. The laser trigger effect is reported here. The effect of XeCl excimer laser operation with high repetition rate is also introduced.

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297. (*)

AUTHORS Yasui, K.

TITLE Plasma Fireballs Fed by Microwaves

TYPE journal

PAGE 451-455

JOURNAL Physics Letters A

VOLUME 173

NUMBER 6

DATE Feb. 22, 1993

KEYWORD ball lightning; microwave; simulation; theoretical

LANGUAGE English

ABSTRACT Ohtsuki and Ofuruton (1991) reported the production of plasma fireballs by microwave interference in air. The experimental conditions were as follows: 2.45 GHz, 5 kW (at maximum) microwaves were guided through a rectangular waveguide into a cylindrical cavity. The cavity was 161 mm in diameter and 370 mm in length. A plasma fireball usually appeared when the microwave oscillator was turned on. Its lifetime varied from 1 s to a few minutes. This experiment is also important in connection with ball lightning. For example, Kapitza suggested that ball lightning is produced by microwave interference in air. The present author has investigated theoretically the experimental results and established a model to calculate their physical quantities.

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298. (*)

AUTHORS Yatsui, K.; Masugata, K.; Kuroda, T.; Ohmomo, Y.; Imada, G.; Satoh, S.; Goto, T.; Yasuoka, K.; Tamagawa, T.

TITLE Breakdown Characteristics in Atmosphere by TEA-CO_2 Laser

TYPE conference

PAGE 671-674

VOLUME 1810

CONFERENCE Proceedings of the SPIE - The International Society for Optical Engineering

LOCATION Crete, Greece

DATE Sept. 21, 1992

KEYWORD experimental; guided; laser; plasma channel

LANGUAGE English

ABSTRACT The breakdown characteristics of a short-distance discharge gap in an atmosphere by TEA-CO_2 laser have been studied to control lightning artificially. It is efficient to enhance the probability of electrical breakdown induced if the focal point is set behind the discharge gap axis or near the negative high-voltage electrode. The length of the optical-breakdown plasma channel is elongated by using the micro-particles diffused in an atmosphere. Using 3 μm diameter aluminum particles, the optical-breakdown threshold is lowered to 15 MW/sq.cm. compared to 0.5 GW/sq.cm. in the absence of the micro-particles.

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299. (***)

AUTHORS Yokoyama, S.; Miyake, K.; Suzuki, T.; Kanao, S.

TITLE Winter Lightning on Japan Sea Coast: Development of Measuring System on Progressing Feature of Lightning Discharge

TYPE journal

PAGE 1418-1425

JOURNAL IEEE Transactions on Power Delivery

VOLUME 5

NUMBER 3

DATE July 1990

KEYWORD basic; experimental; upward leader

LANGUAGE English

ABSTRACT With the aid of recent optoelectronic techniques, the authors have developed a measuring instrument named ALPS (Automatic Lightning Discharge Progressing Feature Observation System) to determine the progress of lightning flashes. The progress velocities of stepped leaders for lightning in winter seasons were observed using the ALPS in the coastal area of the Japan Sea. The progress velocity of and individual step of a stepped leader can be expressed by a lognormal distribution.

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300. (**)

AUTHORS Zipse, D. W.
TITLE Lightning Protection Systems: Advantages and Disadvantages
TYPE conference
PAGE 343
CONFERENCE Proceedings of the IEEE Petroleum and Chemical Industry Technical Conference
LOCATION St. Louis, MO USA
SPONSOR IEEE
DATE Sept. 13, 1993
KEYWORD critique; early streamer emission; multipoint discharge systems; review
LANGUAGE English
ABSTRACT The mechanics and interaction of lightning producing thunder clouds and earth, are discussed. Compared to the Franklin Air Terminal (rod) and Faraday cage, the debatable advantages and disadvantages of the Early Streamer Emission Enhanced Ionizing Air Terminal, and Multipoint Discharge Systems, are examined along with conceptual future methods of lightning production.

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301. (*)

AUTHORS Zischank, W.
TITLE Simulation of Lightning Discharges by Direct Strikes
TYPE journal
PAGE 12-17
JOURNAL Elektrotechnische Zeitschrift ETZ
VOLUME 105
NUMBER 1
DATE Jan. 1984
KEYWORD crowbar spark gap; experimental; practical; simulation
LANGUAGE German
ABSTRACT For the protection against lightning strikes, overvoltage protection devices are required capable of conducting away harmlessly high lightning currents. In order to design and test such protection equipment it is important to be able to develop in the laboratory above average lightning currents. This has been possible to achieve relatively cheaply by the use of the crowbar spark gap in a conventional impulse current generator. The laboratory tests are described and schematically illustrated.

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302. (**)

AUTHORS	Les Renardieres Group
TITLE	Part 4. Effects of Pre-existing Space Charge on Positive Discharge Development
TYPE	journal
PAGE	469-483
JOURNAL	IEE Proceedings-A
VOLUME	133
NUMBER	7
DATE	October 1986
KEYWORD	space charge; gas discharge; leader propagation; air breakdown; corona; experiment
LANGUAGE	English

ABSTRACT

The paper describes one of the three studies with double impulses performed during the fifth test period of the Les Renardieres Group. In the third experiment a negative impulse (T_{cr} = 45 μs) was used to create an extensive space charge in a 6 m rod-rod gap. The voltage level selected was $0.8U_{50-}$. Thereafter the effect of this pre-existing space charge on the development of a subsequent positive discharge was investigated. The positive discharge was initiated by applying a positive impulse (240/2500 μs) to the previously unenergized electrode at the associated U_{50+} level. The spatial and temporal characteristics of the pre-existing space charge were varied over a wide range, first, by utilizing wavetail values of either 180 or 9000 μs and, secondly by selecting the time delay, Δt, to the application of the positive impulse such that Δt lay in the range of 0 to 300 ms. The evolution of the pre-existing space charge is seen to be strongly dependent on the time-to-half value ($T_{1/2}$) of the negative impulse, and, for $T_{1/2}$ = 180 μs, the phenomenon of reverse discharges is observed in the region of the gap adjacent to the negative electrode. Development of the positive discharge is observed to be associated with a leader propagation phase which clearly interacts with the pre-existing space charge, such that the characteristic properties of the leaders (velocity, current) remain essentially constant throughout the test range. The breakdown data (U_{50+}) indicate that large reductions in withstand (approximately 50%) are achieved with the short $\Delta t/T_{1/2}$ values, and that recovery of the gap to an effective space-charge-free condition requires Δt approximately equal to $100T_{1/2}$.

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